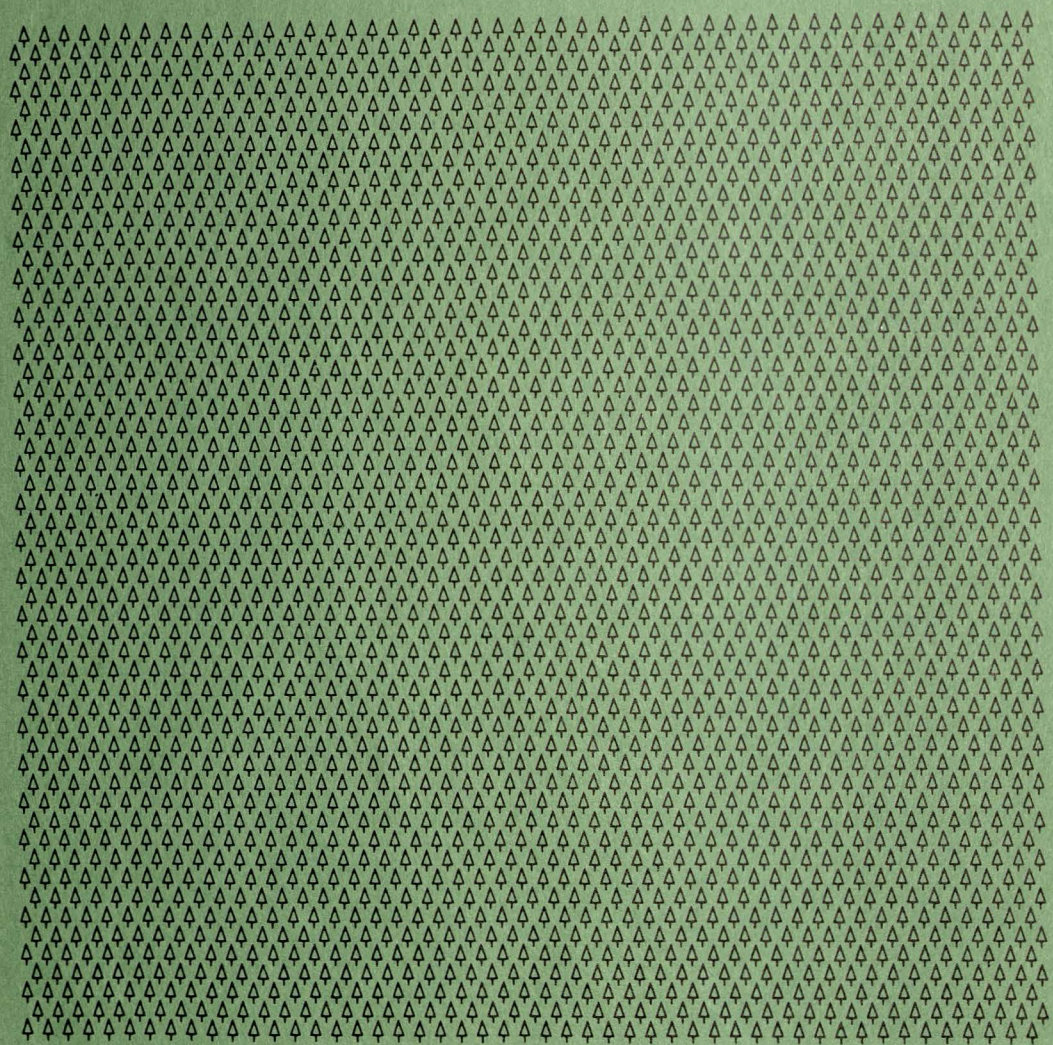
United States
Department of
Agriculture

Forest
Service

North Central
Forest Experiment
Station

General Technical
Report **NC-91**

Intensive Plantation Culture: 12 Years Research



FOREWORD

"Intensive culture" as used in this report is defined as the application of several cultural practices to the establishment and management of plantations with the objective of increasing the quantity and quality of wood produced. The program under review is officially termed the "Research and Development Program: Maximum yield of wood and energy from intensively cultured plantations". It superceded an earlier multiproject program (MPP-II). These programs formed an organizational structure for a multidisciplinary research approach including genetics, physiology, silviculture, soils, entomology, pathology, engineering, utilization, and economics all directed towards a common goal of developing an entirely new silvicultural management system. The research mission of the program is to develop the most biologically efficient and economically feasible method of producing maximum commercial wood per acre by means of a systems approach involving the unified effort of several disciplines. Research was predominantly with hybrid poplar although other species were included throughout the program. This report contains the papers presented at the annual review at the end of the 5-year chartered Research and Development Program. The papers collectively provide a state-of-the-art of intensive culture research and will provide a base for joint planning by managers and researchers for the period ahead.

Each contributor submitted camera copy and is responsible for the accuracy and style of his or her paper.

North Central Forest Experiment Station

Forest Service--U.S. Department of Agriculture

1992 Folwell Avenue

St. Paul, Minnesota 55108

Manuscript approved for publication June 20, 1983

September, 1983

INTENSIVE PLANTATION CULTURE: 12 YEARS RESEARCH

Edward A. Hansen, Compiler

Research partially funded by the Department of Energy under Interagency Agreement #DE-AI05-800R20763.

CONTENTS

Page

The practice and physiological basis of collecting, storing, and planting Populus hardwood cuttings
Anne S. Fege 1
Survival and growth of two intensively cultured jack pine provenances in Tubepak and Jiffy 7 containers
J. Zavitkovski and Howard M. Phipps 12
Mycorrhizae of poplars
R. C. Schultz, J. G. Isebrands, and P. P. Kromanik 17
Effect of Alnus glutinosa on hybrid Populus growth and soil nitrogen contentration in a mixed plantation
Jeffrey O. Dawson and Edward A. Hansen 29
Developing Alnus for use in intensive culture
Richard B. Hall, Gregory A. Miller, Terry L. Robison, and Ochenekome U. Onokpice . . . 35
Irrigating forest plantations
Edward A. Hansen 46
Effect of harvesting season on hybrid poplar coppicing
Terry F. Strong and Jerry Zavitkovski 54
Effect of severing method and stump height on coppice growth
John B. Crist, James A. Mattson, and Sharon Winsauer 58
Growth and Yield of Populus coppice stands grown under intensive culture
Alan R. Ek, John E. Lenarz, and Albert Dudek 64
Projected and actual biomass production of 2- to 10-year-old intensively cultured Populus 'Tristis #1'
J. Zavitkovski 72
Yield physiology of short rotation intensively cultured poplars
J. G. Isebrands, N. D. Nelson, D. I. Dickermann, and D. A. Michael 77
Recent advances in research of some pest problems by hybrid Populus in Michigan and Wisconsin
Lincoln M. Moore and Louis F. Wilson 94
Diseases on intensively cultured hybrid poplars: A summary of recent research in the North Central Region
M. E. Ostry and H. S. McNabb 102
Some implications of Populus intensive culture in nongame birds
Richard L. Verch 110
Synopsis of utilization research of SRIC raw materials
John B. Crist 115
A prototype harvester for short-rotation plantations
James A. Mattson and Michael A. Wehr 119
Prototype wood chunker used in Populus 'Tristis'
Rodger Arola, Robert Radcliffe, and Sharon Winsauer 125
Biomass from intensively cultured plantations as an energy, chemical, and nutritional feedstock
John E. Phelps 131
Economic investigations of short rotation intensively cultured hybird poplars
David C. Lothner 139
Founding concepts for tree breeding and research
Hyun Kang 149

THE PRACTICE AND PHYSIOLOGICAL BASIS OF COLLECTING, STORING AND PLANTING POPULUS HARDWOOD CUTTINGS

Anne S. Fege[1]

Abstract.--Producing healthy hardwood cuttings for Populus plantation establishment requires attention to the management of clonal nurseries, timely collection of cuttings, adequate grading of cuttings, storage temperature and conditions, preplanting treatments, and planting operations. Recommended nursery practices are outlined, along with their grounding in such biological factors as stem anatomy, moisture content, induction of dormancy, availability of carbohydrate reserves, and freedom from insects and pests.

Hybrid Populus plantations can be successfully established with hardwood cuttings of selected, fast-growing clones. Nursery managers and foresters in Europe and North America have a wealth of experience and knowledge about collecting, storing and planting hardwood cuttings, yet our understanding of the biological reasons for these practices is not nearly as thorough. However, physiological studies have offered many generalizations about cutting production that have further refined nursery practices. The empirical knowledge of each of the practices involved in producing healthy cuttings and the physiological bases for these practices are summarized in this paper, drawn principally from the literature on Populus and on our experiences at the Forestry Sciences Laboratory in Rhinelander, Wisconsin.

The recommended production practices are a sequence of activities, beginning with the establishment of clonal nurseries, as represented in Figure 1. All of these practices are directed toward the ultimate objective of producing trees that have high survival rates and maximum vigor and height growth, particularly during the first growing season. With early rapid growth, the time is reduced that costly weed control treatments are required and that terminal shoots are out of reach of browsing deer.

The findings reviewed in this paper are limited to hardwood cuttings of Populus clones that root easily from hardwood cuttings. Because of their stem anatomy, roots begin to emerge from the bark of these cuttings within several days of

Figure 1.--Required practices and factors affecting the production and establishment of healthy cuttings.

CLONAL NURSERIES	→ COLLECTION	→ CUTTING SELECTION	→ STORAGE	→ PRE-PLANT TREATMENTS	→ PLANTING OPERATIONS	→ HEALTHY PLANTATIONS
Establishment Nutrition of Parent Plant Pest Management	Time of Year Equipment	Diameter Position Absence of Disease or Wounds	Duration Temperature Conditions Moisture Pathogens	Duration Soaking in Water Fungicide Dips	Site Preparation Soil Moisture Planting Equipment Weed Control	

1/ Graduate Research Assistant, Department of Forest Resources, University of Minnesota, St. Paul, MN

soaking in water. One-year-old stems and some older wood of poplars (Populus sections Aigieros and Tacahamaca), willows and other species have performed root primordia, which generally originate in ray tissue of the secondary phloem (Braun 1963, Haissig 1974, Hartmann and Kester 1975, Swingle 1929, and Smith and Wareing 1972a). These adventitious roots only need to increase in length and size. Wound roots may also be produced from the base of the cutting, sometimes following callus formation. These wound roots are relatively unimportant in species with preformed root primordia, but become the adventitious roots in species and plant material that lack preformed root initials. Cuttings of the Leuce section of Populus have few preformed primordia, and are much more difficult to root (Farrar 1977, FAO 1979). Many Populus clones can also be propagated from roots, suckers, or grafts (FAO 1979, Hartmann and Kester 1975, and Williams and Hanks 1976). Softwood (or greenwood or tip) cuttings taken from non-dormant rapidly-growing shoots have received most of the attention in empirical and physiological studies of cuttings. Research efforts on softwood cuttings, and on hardwood cuttings of species or plant material that lacks preformed root primordia, have been directed toward altering environmental conditions and applying chemicals (usually hormones such as auxin) that promote root initiation.

Clonal Nursery Management

Managers who plan to establish large plantations or who want to control the quality and availability of hardwood cuttings should install and maintain their own clonal nurseries. Each hectare of Populus plantations established at spacings of 1 m^2/tree requires 10,000 cuttings (4,000/acre), and 2500 cuttings for spacings of 4 m^2/tree (1,000/acre), so large numbers of cuttings must be produced and handled.

Generally, 4 to 10 whips are produced from each rootstock, and 5 to 8 20-cm cuttings can be obtained from each whip (depending on the clone and shoot condition), thus each healthy rootstock could yield from 20 to 80 cuttings annually. A clonal nursery established with 1 or 0.5 m between trees within rows and 1 m between rows allows plenty of room for tractors and equipment used for harvest of cuttings (Hansen, Moore, Netzer, Ostry, Phipps and Zavikovski 1982). About 10,000 rootstocks could be maintained per hectare, and about 200,000 cuttings produced per hectare annually. Additional acreage must be allotted to roads and irrigation lanes, and some consideration given to the failure of rootstocks to resprout. For Populus plantations established in the southern United States, McKnight (1970) recommended that clonal nurseries be established with 0.3 m spacings within rows and 1 m between rows, to maximize production of unbranched whips. Many clonal nurseries are also established at wider spacings, typically 1 m between trees within rows and 3 m between rows, which facilitates cultivation and increases the number of whips produced per rootstock. Spacings of up to 3 m between rows reduce incidence of some diseases such as Septoria canker and allow sanitation practices such as disposal of infected residues and soil cultivation to be undertaken more easily (Hansen et al. 1982).

Maintenance of healthy nursery plants is essential, since cutting vigor has been related to nutrition of the parent shoot (FAO 1979, Hartmann and Kester 1975). Clonal nurseries at Harshaw Experimental Farm (10 miles west of the Forestry Sciences Laboratory, Rhinelander, Wisconsin) have been established from disease-free hardwood cuttings, fertilized, irrigated, and maintained weed-free by mechanical cultivation and herbicides. McKnight (1970) recommended that a well-drained site be chosen, and that nursery beds be fumigated if cottonwood had been grown there previously. The Food and Agriculture Organization publication Poplars and Willows (1979) recommends that nurseries be established on fertile, well-drained soils; fertilized; maintained free of weeds; and protected against insects and disease. Clones which are particularly susceptible to diseases should be removed from the clonal nursery.

After 1 or 2 years, the planted trees are cut back to within 15 cm of the ground, and the resultant coppice growth harvested annually thereafter for cuttings. Rootstocks can normally be maintained for 4 to 8 years until sprouting vigor is markedly reduced. Although the author knows of no study on the longevity of Populus nursery rootstocks, there have been some studies on the effect of season of harvest and cutting method on coppice regeneration of plantations. DeBell and Alford (1972) reported that sprouting vigor was greatest when harvests were made during the dormant season, as would be the case for cutting production, and that cutting height and angle had no effect on initial sprouting of stumps established from P. deltoides cuttings. Hansen et al. (1982) recommend that stumps be cut 15-20 cm above the ground each year. Phipps (personal communication) offered the observation that some sprouts grow nearly horizontal to the ground when stumps are cut nearly at ground level. Lust and Mohammady (1973) suggested that rupture of the bark and bursting of the stool be avoided, that the cutting surface be as close to the soil as possible so that some shoots develop their own root systems, and that the cut be smooth and angled so that water can run off. Crist and Mattson[2/] found that stump mortality was

[2/] Crist, J. B., J. A. Mattson and S. A. Winsauer. 1983. Effect of severing method and stump height on coppice growth. This publication.

significantly greater for Populus 'Tristis #1' trees severed in February with a shearing head than for stumps sawn with a chain saw, with some mortality caused by shearing head's damaged to adjacent stumps.

Collection of Cuttings

Collecting and sorting cuttings is still labor-intensive, and there are many opportunities for reducing labor requirements and costs of processing cuttings. At the Harshaw Experimental Farm, a side-mount sickle bar mower is used, that has a sharp bar and is in good operating condition, to minimize ragged cuts, splitting, and other damage to stumps. The mower is followed by a tractor-drawn wagon, onto which two workers load the harvested whips. Harvest systems are being developed that will cut whips, tie them in bundles and load them onto wagons for transport to the processing area (Hansen et al. 1982).

Hardwood cuttings must be collected after shoots achieve some degree of dormancy and before the end of dormancy is reached in the spring. Most commercial nurseries collect hardwood cuttings from December to early March, as displayed in Table 1.

In regions where snow cover and cold temperatures hamper the ability of field crews to collect cuttings in mid-winter, cuttings may be collected in late fall. In the fall of 1980, hardwood cuttings of 7 hybrid Populus clones (whose parentage is listed in Table 2) were collected monthly from the Harshaw Experimental Farm from mid-September to mid-December. Cuttings were stored over the winter at temperatures from 2 to -20°C, and planted in mid-May (Fege and Phipps 1982). A similar study was conducted the following year, with cuttings of 3 clones collected in mid-October and mid-December, stored at 3 temperatures, and planted in May. As shown in Table 3, survival was poor for all cuttings collected in September. Survival and height of cuttings collected in mid-October were not significantly different from cuttings collected in November or December for any of the clones, with the exception of clone group 5262 collected in mid-October and stored at -20°. Bud set was 2 weeks later for clone group 5262 than clone group 5334 or clone 5260, and this suggests that plant material of clones 5262, 5263, 5272, and 5377 was not sufficiently hardened by mid-October to withstand -20° temperatures. In the 1981-82 study, overall height growth was much less for all treatments and clones because of lower temperatures in June and poor weed control in the plots, but survival patterns were similar. Whereas overall survival of clone 5260 was poor in the 1980-81 study, its performance paralleled that of clone 5334 in 1981-82.

Some studies of effects of collection date must be interpreted cautiously, since cuttings were planted in greenhouses immediately after they were taken from the field. Field managers would not be able to plant cuttings in January or February. Yet, these studies offer additional insight into the physiological conditions of parent material during the winter. Allen and McComb (1956) found greater survival and rooting of cuttings collected in March and planted immediately, than those collected and planted in November or December. Farmer (1966) found that Populus deltoides cuttings collected in Mississippi in early February rooted better than those cut in December, January or early March, when planted immediately after collection. Phipps and Netzer (1981) collected cuttings of 4 clones monthly from November to March and planted them immediately in a greenhouse, and found that rooting and bud break occurred more rapidly in the later-collected cuttings, and that the lowest rate of rooting was for cuttings collected in November. Cuttings collected in November and stored at 2.8°C for 5 months had the same rate of rooting as March-collected cuttings, suggesting that proper storage may permit earlier collection of cuttings with no loss of rooting ability.

Some degree of dormancy must be achieved before cuttings are harvested. Physiological changes accompanying the process of dormancy induction include cessation of growth, increase in stored reserves, development of cold hardiness, and leaf fall. Our studies have shown differences in carbohydrate content in dormant Populus shoots throughout the winter.[3/] Starch content is greatest in early fall, and declines progressively to minimum levels in December through early March. Content of total sugars increased from September to December, maintaining high levels until early March. Although a direct relation between carbohydrate content and field performance has not been established, we assume that these carbohydrate reserves provide the energy for early growth and emergence of functioning roots.

Selection for Cutting Size and Position

Entire whips are generally sawn into cuttings of about 20 cm in length, then sorted and bundled. After entire whips are brought in from the field, branches are clipped from the mainstem and discarded, then 4 to 6 whips are held together and sawed into 20-cm lengths with a band saw. The small-diameter shoot tip and any portion of the stem base which is less than 20 cm in length is

---

3/ Fege, A. S. and G. N. Brown. 1983. Carbohydrate distribution in dormant Populus shoots and hardwood cuttings. In preparation for Forest Science.

Table 1. Commercial nursery practices for collection and storage of *Populus* hardwood cuttings.[1/]

	Collection Date	Storage Conditions	Planting or Shipping Date
1.	January and February	Stored as cuttings, covered with moist peat moss, at 1 to 2°C, or uninsulated barn as low as -7°C.	May
2.	Late winter, while still dormant	(Planted as soon as possible; kept in cellar until planting.)	
3.	Mid-December through February	Stored as cuttings in wet peat moss or shingletoe in wooden crates lined with plastic (10 bundles of 100 cuttings/bundle in each crate) at -3 to 0°C.	Late April to June
4.	February and March	Bundles of 15-cm cuttings dipped in Chlorox, put in wet peat/sand mixture, at 1 to 2°C in 100 percent humidity room.[2/]	After last frost (May)
5.	January and February	Bundles of 150 15-cm cuttings dipped in Captan-Benlate solution, and 6 to 8 bundles stored in 30-gallon plastic trash bags at -1°C.	May
6.	Mid-December to late February	Stored as cuttings in plastic bags held in cardboard boxes at -2°C (bud break occurs in cuttings stored at 0 and 2°C).	Late March to late May
7.	November and December	Stored as bundles of 12-cm cuttings placed in wooden flats with basal ends in moist sphagnum moss. Held at 10 to 15°C for 2 weeks to initiate callus formation and roots, then stored at 1°C.	Mid-May
8.	December	Stored as entire whips in humidity-controlled room, at -2°C until March. Whips sawed into cuttings, bundles dipped in fungicide and stored at 1°C in mulch until planting.	Late April
9.	December	Whips harvested in December, sawed into cuttings in January, and stored in plastic bags below 0°C.	April and May
10.	December and January	Stored as 32-cm cuttings in plastic bags in unheated barn. In late February, cuttings moved to cold storage at -1°C.	May and June
11.	During dormancy[3/]	Stored as cuttings at -2 to 0°C, bundles set in 5-7 cm of moist sand, covered with wet burlap. If cuttings taken immediately before planting, cuttings are held in aerated ponds for 3 days or more.	December to early March (southern U.S.)

1/ Nurseries located in Maryland, Michigan, Minnesota, Montana, Ohio and Pennsylvania.

2/ Mention of commercial products does not constitute endorsement by the University of Minnesota or the U.S. Department of Agriculture.

3/ From McKnight (1970).

Table 2. Parentage of hybrid *Populus* clones.

Original Number	North Central Number	Parentage[1/]
---	5260	(*P. tristis* x *P. balsamifera*) 'Tristis #1'.
NE-387	5262	*P.* 'Candicans' x (*P.* x *berolinensis*)
NE-386	5263	*P.* 'Candicans' x (*P.* x *berolinensis*)
NE-1	5272	(*P. nigra* x *P. laurifolia*) 'Strathglass'
NE-252	5334	*P. deltoides* var. *angulata* x *P. trichocarpa*
---	5377	*P.* x *euramericana* 'Wisconsin #5'
---	9922	*Populus* spp.

[1/] From Hansen *et al.* (1982). Names according to Dr. Donald Dickmann, Department of Forestry, Michigan State University, East Lansing, MI. 48824.

Table 3. Field performance of hardwood *Populus* cuttings, by date of collection and storage temperature.

Date of Collection	Percent Survival 2	-3	-10	-20	Height of Surviving Trees (cm)[1/] 2	-3	-10	-20
1980-1981 Study								
5262 group[2/]								
September	76	0	1	0	87	-	-	-
October	86	92	94	14	111	107	115	-
November	100	93	93	97	111	106	113	111
December	95	96	95	96	97	114	111	115
5334 group[3/]								
September	77	7	0	0	78	-	-	-
October	87	90	88	78	101	97	103	82
November	72	62	53	78	77	65	75	80
December	97	90	82	88	85	108	95	92
Clone 5260								
September	7	10	23	0	-	-	-	-
October	30	3	100	93	-	-	61	74
November	17	7	93	97	-	-	68	59
December	53	37	97	63	-	-	71	49
1981-1982 Study[4/]								
Clone 5262								
October	65	70	20	-	33	45	-	-
December	82	85	75	-	57	45	42	-
Clone 5334								
October	92	88	75	-	35	36	25	-
December	98	92	82	-	45	37	35	-
Clone 5260								
October	92	80	100	-	21	26	36	-
December	90	86	80	-	20	22	29	-

[1/] Generally for treatments with greater than 60 percent survival.

[2/] Clones 5262, 5263, 5272 and 5377.

[3/] Clones 5334 and 9922.

[4/] Cuttings held at 2, -3 and -10°C in 1981-1982 study.

discarded. At most nurseries and research stations, teams of workers sort cuttings manually. Careful labeling of the clone number for each batch of cuttings is essential. At Harshaw Experimental Farm, cuttings that do not meet the following grading standards are discarded: (1) diameter greater than 0.95 cm, (2) no evidence of mechanical damage such as stripped bark, split or crushed ends, or broken or missing buds in the top third of the cutting; (3) no signs of disease or insect infestation such as fruiting bodies, galts, lesions, eggs, or borers; and (4) green inner bark and no dessicated or shrivelled outer bark. The acceptable minimum and maximum diameter values vary by clone and generally are set to exclude the terminal cutting and cuttings made from the upper portions of small-diameter whips. All cuttings should be oriented in the same direction, to eliminate the need for such orientation by the planting crew.

Two well-accepted generalizations may be made about cuttings: larger cuttings perform better than smaller cuttings, and cuttings taken from the shoot terminus root poorly. However, it is difficult to separate the effects of cutting diameter, cutting length, and position of the cutting within the parent shoot. Larger-diameter cuttings had higher survival rates and produced taller shoots and shoots with greater dry weight, in studies with 20-cm cuttings in Michigan and Wisconsin (Dickmann, Phipps and Netzer 1980). Clonal response differed greatly, with shoot height differences of 14 percent between largest- and smallest-diameter cuttings for one clone, and 250 percent for another clone. For 3 of the clones tested, survival was 20 to 40 percent less for cuttings with diameters of less than 6 mm, suggesting that this may be a minimum diameter for cuttings used in field plantings of many clones. Bowersox (1970) found that height growth was correlated with cutting diameter for the first 2 years after planting, but height after 3 years was not related to cutting diameter.

Rooting and field performance of planted cuttings varies with distance from the shoot tip. Bloomberg (1963) observed that rooting capacity of Populus clones increased with distance from stem tip, and reported that basal cuttings of 3 Populus clones had significantly greater root number, total length and weight of roots than cuttings taken from the second 15-cm length from the tip. Hansen and Tolsted (1981) found that cuttings taken from branches, 1-year-old and 2-year-old stemwood of a difficult-to-root clone (P. alba) had comparable survival rates for any given diameter class as cuttings taken from the main stem (Table 4). Cutting survival increased as cutting diameter of both stem and branches increased, and was essentially due to the effects of position. They recommended that branch material be selected on the basis of diameter, but stem material be selected on the basis of both diameter and position, since some of the smaller-diameter basal cuttings still had high survival rates. Height growth increased with cutting diameter for the first 2 months that plants were grown in the greenhouse, but no further effect on height growth was observed. Allen and McComb (1956) found that, with constant cutting diameter, cutting survival and number of roots decreased with age of the parent shoot. They found no survival differences for cuttings of three diameters (0.52, 1.12, and 2.1 cm).

The effect of diameter and stem position on field survival may be attributed to many anatomical and physiological factors. Smith and Wareing (1972a) have shown that preformed root primordia develop acropetally in 1-year-old Populus x robusta coppice shoots throughout the summer and fall, thus root primordia in basal regions develop earlier. Bloomberg (1962) has shown that the anatomy of the basal region of 3 Populus hybrids had wider and fewer vessels than the top region, wider sieve tube zones, and a thicker periderm, thus is more favorable for water storage, retention and translocation. Total carbohydrate reserves are also greater in larger-diameter cuttings. Bud development varies widely along 1-year-old Populus stems with poorly developed buds at the stem base. In addition to developing into the new shoot, these buds also affect root development. Smith and Wareing (1972b) found that removing buds from Populus x robusta cuttings decreased the emergence of root primordia.

Table 4. Relation of cutting numbers and survival to cutting diameter, after 3 months.[1/]

	Stem and Branches		Stem		Branches	
	#Cuttings	% Survival	#Cuttings	% Survival	# Cuttings	% Survival
All cuttings	357	29	144	39	213	22
Greater than 9 mm	102	53	85	53	17	53
Greater than 15 mm	20	65	-	-	-	-

[1/] Hansen and Tolsted (1981).

Cuttings are commonly 20 cm (8 inches) in length, although longer cuttings are known to survive better than shorter cuttings under such conditions as moisture stress in the field. On shallow soils, shorter cuttings are generally recommended, and on deeper soils, greater survival will be achieved with 50- to 80-cm cuttings inserted to a depth of 30 to 40 cm (FAO 1979). McKnight (1970) advocated 50-cm cuttings for establishing Populus deltoides plantations in the South. Allen and McComb (1956) found that survival, number of roots and shoot growth of 45-cm cuttings was at least double that of 15-cm cuttings.

Parent stems and cuttings should be examined for disease signs, since pathogens causing blackstem, cankers and rusts may be disseminated on planting stock. Blackstem (caused by the fungi Phomopsis, Cytospora and infrequently Dothichiza) can cause deterioration of cuttings, killing them directly in storage or reducing their vigor after planting. Ostry and McNabb (1982) have reported that the presence of each pathogen differed on cuttings collected in Iowa and Wisconsin. The incidence of many Populus diseases and insect pests varies widely by region and locality. Marssonina and Septoria and insect eggs and borers can be present in cuttings, and entire plantations infected if diseased or infested cuttings are planted.

Storage Temperature and Conditions

Most commercial nurseries store cuttings successfully just below or at 0°C for 2 to 4 months before planting (Table 1). Our experience has been that sprouting and root emergence occurs if cuttings are stored just below or above freezing for 5 to 8 months before planting time. For these longer storage periods, cuttings should be held at -10°C or lower to avoid root and shoot development before planting. Cuttings are commonly stored in bundles in one of three microenvironments: (1) moist sand or peat moss around the basal quarter to half of the cutting, covered with moist burlap or held in a humidified environment; (2) in plastic bags in environments where humidity is not controlled; or (3) as entire whips in humidity-controlled rooms.

Generally greater survival and field performance have been achieved by storing cuttings at temperatures several degrees below freezing. For those cuttings stored considerably below 0°C, certain pre-planting treatments may be required for satisfactory growth. Phipps and Netzer (1981) found that cuttings of 4 clones collected in early November rooted and flushed more rapidly if cuttings were stored at 2.8°C than if they were stored at -17.8°C or -3.9°C. This growth retardation was overcome in cuttings stored for one year at -7°C by pre-conditioning the cuttings for 1 or 2 weeks at 2°C then soaking the cuttings until roots began to emerge (Phipps, Hansen and Fege 1983). Phipps and Netzer (1981) found that cuttings of 3 Populus clones stored for 4 months at -18°C and -6°C rooted slower than those stored at either 3°C for 4 months, or at 7°C for 2 months followed by 3°C for 2 months. Nearly 100 percent of the cuttings rooted within 22 days of planting, regardless of storage temperature. Cram and Lundquist (1982) found no significant differences between height of cuttings of the Walker clone (Populus x deltoides Bart. cv. 'Walker') stored at -2°C and 2°C over the winter. However, they reported 82 percent "rooting capacity" of cuttings stored at -2°C from mid-November to mid-May, compared with 73 percent after storage at 2°C and 60 percent after heeling-in outdoors over the winter.

In our studies of 7 Populus clones collected in mid-October or later and stored at temperatures from 2°C to -20°C in 1980-81 planted in 1981, and 3 clones stored from 2°C to -10°C in 1981-82, there were no statistically significant survival or height differences by storage temperature, except that some clones collected in October and stored at -20° or -10°C did not survive (Table 3). The pre-planting treatments of "warming" and soaking may have obscured the differences between cuttings stored at various temperatures. For the 1980-81 and 1981-82 studies, cuttings stored at -10°C and -20°C were transferred to 2°C about 3 weeks and soaked in water 1 week prior to planting; cuttings stored at 2°C or -3°C were soaked only 1 day since shoots and roots had begun to grow during storage. Since cuttings stored at the two lower temperatures achieved the same height growth as cuttings stored at near-zero temperatures, the -10°C and -20°C storage temperatures would be advantageous for field operations, since they allow nursery managers greater flexibility in soaking cuttings and scheduling planting.

Minimizing the incidence of disease is an advantage of storing cuttings at freezing temperatures. Development of molds and other organisms on hardwood cuttings and seedlings during storage reduces field survival. Generally, damage is more common when plants are collected early in the fall, storage temperature is above freezing, temperature of storage chamber is allowed to fluctuate, free moisture is present on plant surfaces, and/or storage period is extended several months (Venn 1980). Ostry and McNabb (1982) have shown that incidence of blackstem fungi is lower and survival of cuttings of two hybrid Populus clones is higher when cuttings were stored at -3°C rather than at 1°C. Cytospora was associated with lower bark moisture in these cuttings.

Cuttings can be bundled and packed in moist sand or peat moss if the storage room has high humidity or if damp burlap covers the cutting bundles. Otherwise, cuttings should be kept in plastic bags during storage. In a study of 5 hybrid Populus clones stored at two locations,

cuttings were stored in mulch or plastic bags, or stored as entire whips. For the 3 clones, survival and height growth did not differ significantly between locations or treatments.[4/] For the other 2 clones, there were no differences in either survival or height growth between treatments, with the exception that none of the cuttings stored in the less-controlled environment at Harshaw Farm survived. Cram and Lindquist (1982b) observed that Populus cuttings covered with vermiculite or stored in polyethylene bags at temperatures of -5°C or -1°C showed greater rooting than those stored as bare cuttings, whereas there was no difference between the 3 storage methods at -18°C.

Moisture content in cuttings is influenced by storage conditions. Ostry and McNabb (1982) observed that cuttings stored in plastic bags retained more moisture than those stored unbagged, and resulted in better field survival. In our study of 5 Populus clones stored at 2 locations, moisture content averaged 148 percent for cuttings stored in mulch, 118 percent for those stored in plastic bags, and 84 percent for those stored as entire whips. Cram and Lindquist (1982a) found moisture content to be 136 percent in November-collected cuttings heeled-in outdoors during the winter, with 108 to 123 percent moisture content in cuttings stored at 2°C in plastic bags and 108 percent in cuttings stored at -2°C in plastic bags. It is common practice in France to dip both ends of cuttings in paraffin wax to reduce dessication, with colored wax used to identify the cuttings of different clones (FAO 1979).

Pre-Planting Treatments

The bottom half or three-quarters of cuttings should be soaked in water at about 15°C for 7 to 10 days before planting, until root primordia begin to emerge from the bark and cuttings are fully imbibed. Cuttings may be soaked outdoors in the shade, or in an equipment shed. If cuttings have been stored in plastic bags, the bottom and top of each bag may be punctured to admit water. If roots have begun to emerge and shoots begin to grow during storage, cuttings should be soaked only one day before planting so that moisture content is increased but shoots and roots do not develop further. In order to determine the number of days of soaking needed for root emergence to begin, small tests should be conducted with each clone and storage treatment about a month before planting is scheduled. Nursery managers should soak the cuttings until roots appear as small bumps under the bark surface and begin to break through the bark.

Soaking increases early root growth, essentially extending the growing season. Soaking cuttings for 10 days would be equivalent to a 10 percent increase in the 100-day growing season in northern Wisconsin (Phipps, Hansen and Fege 1983). Petersen and Phipps (1976) found that presoaking stimulated rooting and increased field survival of hardwood cuttings of 3 Populus clones. Root length, root dry weight, percent flush and shoot length increased with duration of soaking (Phipps, Hansen and Fege 1983). In studies of Populus and Salix poles (1.4 to 2.7 m long), Edwards and Kissock (1975) reported that water uptake was most rapid in the first 1-3 days, then followed a logrithmic decline, and that water uptake was maximized by soaking stems vertically rather than horizontally. Shoot and root growth and drought resistance was increased by soaking. Soaking P. deltoides cuttings for 24 hours prior to planting is cited as a method for reducing Dothichiza (FAO 1979), presumably due to the increased moisture content at planting.

Generally, root development proceeds faster at temperatures of about 15°C and under conditions of saturated moisture content. For cuttings which are partly immersed, water should be changed every 2 days or aerated, since oxygen is required for root development. Bloomberg (1963) found that roots produced by cuttings which had moisture content adjusted to 100 percent saturation within polyethylene bags had 5 to 10 times more roots, about twice the total length of roots, and up to 9 times the root dry weight of those produced by cuttings at 50 percent moisture content. When Phipps, Hansen and Fege (1983) made comparisons between soaking 20-cm cuttings to depths of 3 or 15 cm, no significant difference was found for 3 clones, and slightly greater root length and dry weight for only 1 clone, when soaked to 15 cm. Water uptake, bud break, and the emergence of roots proceeded faster in cuttings which were soaked in the dark at 16°, compared with those soaked at 4°C. Bloomberg (1963) held cuttings in polyethylene bags which had moisture content adjusted to fully saturate the cuttings, and found that root number, length and dry weight after 10 days were much lower when cuttings were kept at 5°C, than if they were kept at 15°C or 25°C.

Following observations that soaked cuttings performed far better than unsoaked cuttings when spring weather was exceptionally warm and dry, Phipps and Hansen (1983) evaluated the effects of soil moisture tension on cutting development. Soaking for 4 to 10 days accelerated bud flush over the range of soil moisture tensions (0 to -0.6 bars), with increased shoot length at the high soil moistures. None of the unsoaked cuttings at -0.5 bars flushed by 10 days after

4/Fege, A. S. and H. M. Phipps. 1983. Effect of collection date and storage conditions on field performance of Populus hardwood cuttings. In preparation for Can. J. For. Res.

planting. In field studies of cuttings planted at various dates from snow melt to frost, tree height of soaked cuttings was 13 percent greater than unsoaked cuttings during a wet spring. Allen and McComb (1956) observed 0-20 percent survival in soils at or below field capacity and 61-80 percent survival in soils at moisture contents up to full saturation for 47 days, for unsoaked cuttings. Soaking 50-cm Populus deltoides Bartr. cuttings significantly increased field survival, but the advantage of soaked over unsoaked cuttings were much greater when field conditions were less desirable (Krinard and Randall 1979).

There is some flexibility in the number of days that cuttings can be soaked before planting, depending on the winter storage temperatures and field moisture conditions. When cuttings have reached the proper stage for planting, they may be stored on crushed ice for up to 2 weeks to delay further root extension and shoot development (Phipps, Hansen and Fege 1983). Shoot growth for 4 weeks following planting in soil with adequate moisture was not affected by allowing soaked cuttings to dry for 8 hours at 24°C before planting. After allowing Populus cuttings to dry out for 8 to 14 days (lowering moisture content by 22 to 24 percent), then soaking cuttings in water for 1 day before planting, Bogdanov (1965) reported survival levels of 60 to 75 percent of cuttings which had not been allowed to dry out. In our studies with 7 Populus clones during 2 growing seasons, the cuttings stored at 2°C or -3°C had emergent roots and some flushed buds. Soaking for more than 1 day or delaying planting would have increased mortality of these cuttings. McKnight and Biesterfeld (1968) reported that two companies in the South stored entire whips for a few days in bulldozed trenches filled with water at the planting site, with whips cut into 50-cm lengths just before planting. The basal ends of cuttings were sometimes placed in ditches for a few days before planting, with wet burlap sacks covering them.

When cuttings have been soaked too long and roots have emerged, the process of planting cuttings will break off or damage many of these initial roots. After removing 75 percent and 100 percent of the roots emerging from Populus trichocarpa cuttings which had been incubated in darkness in moistened plastic bags, Bloomberg (1963) reported significantly less shoot growth and fewer roots in the first 9 months, when compared with cuttings planted with all the initial roots intact. Cuttings with 75 percent of their roots removed suffered no greater mortality and had the same root dry weight as cuttings with all their roots intact.

Treatment with fungicides may lessen disease incidence, and indeed, several commercial nurseries included in Table 1 dip their cuttings in fungicides before storage. Hartmann and Kester (1975) recommend that cuttings be dipped in 5 percent benomyl or 24 percent captan after cuttings are made. Two clones known to be susceptible to blackstem injury in early trials were treated with 2 fundicides (1200 ppm) and stored from early March to early June at -20°C, -3°C, and 1°C. Average survival was 58 percent for untreated controls, 70 percent when treated with thiram and 81 percent when treated with benomyl (Ostry and McNabb 1982). Blackstem damage was much lower in cuttings stored at -3°C than those stored at 1°C, and storage of cuttings at -3°C eliminated the need for fungicide use. Ostry and McNabb (1982) also reported that fungicide dips increased survival at 2 sites where adverse growing conditions were found, but that there were no differences at 2 other sites where growing conditions were favorable. Since blackstem develops only on stressed cuttings, they conclude that fungicide dips are not necessary if healthy cuttings and proper handling and storage practices are used, and sufficient water and nutrients are supplied after planting.

There have been various reports of more rapid rooting when auxins are added to the soaking water. Only limited benefit would be achieved in most clones that have performed root primordia since roots emerge after cuttings are soaked in water for a week, but there is evidence that rooting is stimulated in clones which have fewer preformed root primordia (Hartmann and Kester 1975).

Planting Cuttings

Hardwood cuttings should be planted vertically with only 1 or 2 cm of the top of the cutting exposed, and soil well-packed around the cutting. In tests designed to determine the effects of cutting length and planting depth, the least number of main shoots were produced when 20-cm cuttings were planted flush with the ground surface in a silt loam soil. However, first year shoot height was less than that of cuttings planted at shallower depths of either 10 to 15 cm (Hansen et al. 1982). Horizontal planting of cuttings has also been evaluated for various species, but is not generally recommended for Populus. Bloomberg (1963) found that significantly more roots were produced by P. x regenerata and P. x robusta cuttings when placed in upright rather than inverted or horizontal positions, but there was no effect of planting position on P. trichocarpa cuttings.

Cuttings are planted in the spring, after the frost has left the ground and site preparation is completed. This may be as early as March in warmer climates and as late as early June in the northern U.S. Over 3 years, Hansen et al. (1982) found that cuttings planted in mid-May grew consistently more during the growing season than those planted in April, but that differences between planting dates from April to early June were slight. Fall

planting was successful in only 1 of the 3 years due to frost heaving; snowpacks were light in both years that fall planting failed.

Research foresters at the Harshaw Experimental Farm have established up to 8 ha annually with 2 modified planting machine systems. The first consisted of 4 semi-mechanical transplanters model CT-5 mounted on a 15-ft tool bar, pulled by a 85-hp farm tractor. Each of the 4 units can plant about 1200 cuttings per hour at a 1-meter spacing. In a time study of this system, 30,400 cuttings were planted in a 2.9 ha Populus plantation at 1 x 1 m spacing (Mattson and Miyata 1982). The actual planting required 5.6 hours and the estimated planting costs were $98/ha, with lower costs projected for wider spacings. The second planter consisted of 2 Holland transplanter units Model 1525. This was also pulled by a 85-hp tractor. Each unit planted approximately 500 trees per hour. Engineers at the Forestry Sciences Laboratory in Houghton, Michigan, have modified the planter by adding an audible system to control within-row spacing, redesigned the packing system, added larger and stronger planting shoes, and added protective shields for the operators (Hansen et al. 1982). Spacings must be precisely maintained, particularly between rows, in order to facilitate cultivation and minimize damage to stems whenever equipment is maneuvered between the planted rows. For planting 50-cm P. deltoides cuttings, the Southern Forest Experiment Station developed a slit-planting machine that opens a trench with a subsoil chisel, with one worker riding the machine and manually inserting cuttings to the bottom of the trench at the proper within-row intervals. The machine was mounted on a 3-point hitch and drawn by a tractor of at least 85 drawbar horsepower (McKnight and Biesterfeld 1968). During field operations, moisture content of unplanted cuttings should be retained by covering cuttings with moist burlap or by leaving cuttings in plastic bags, and holding cuttings in the shade.

The survival and growth of planted cuttings depends greatly on the availability of soil moisture in the soil or the supplementation of soil moisture by irrigation. In a growth chamber study, Phipps, Hansen and Fege (1983) found that the time required for bud break and early shoot growth increased as soil moisture tentions decreased. Whereas adequate soil moisture is particularly important in the weeks following planting, field performance during the first growing season depends also on adequate moisture, control of competition, soil nutrient levels, and pest management.

Conclusions

Hardwood cuttings are routinely collected, stored and planted by many nurseries in Europe and North America to establish Populus shade trees and plantations. For all the activities required for cutting production, from managing clonal nurseries to planting the cuttings, there are recommended practices based on both practical experiences and knowledge about physiological processes. There is considerable flexibility in some of the practices, particularly in the clonal nursery design, date of cutting collection, sawing and sorting procedures, and duration of soaking cuttings. On the other hand, planting stock vigor and survival can be markedly reduced if storage temperature and duration are not considered together, if there is inadequate soil moisture, and if cuttings are infected with blackstem diseases. These practices are only recommendations--each nursery must tailor their operations to their region, site, field workers, and Populus clones.

LITERATURE CITED

Allen, R. M. and A. L. McComb. 1956. Rooting of cottonwood cuttings. USDA For. Serv. Occas. Paper 151, So. For. Exp. Sta., 10 p.

Bloomberg, W. J. 1962. Cytospora canker of poplars: The moisture relations and anatomy of the host. Can. J. Bot. 40:1281-1292.

Bloomberg, W. J. 1963. The significance of initial adventitious roots in poplar cuttings and the effect of certain factors on their development. For. Chron. 39:279-289.

Bogdanov, P. L. 1965. Poplars and their cultivation. U.S. Dept. of Commerce Clearinghouse for Federal Scientific and Technical Information. Springfield, VA. TT 68-50374, 89 pp.

Bowersox, T. W. 1970. Influence of cutting size on juvenile growth and survival of hybrid poplar clone NE-388. Tree Planter's Notes 21(4):1-3.

Braun, H. J. 1963. Wurzelkeime in jungen und älteren Sprossachsen von Populus. Z. Bot. 51:441-451.

Cram, W. H. and C. H. Lindquist. 1982. Overwinter of Walker poplar cuttings. For. Chron. 58: 175-177.

DeBell, D. S. and L. T. Alford. 1972. Sprouting characteristics and practices evaluated for cottonwood. Tree Planter's Notes 23:1-3.

Dickmann, D., H. Phipps and D. Netzer. 1980. Cutting diameter influences early survival and growth of several Populus clones. USDA For. Serv. Res. Note NC-261, 4 pp.

Edwards, W. R. N. and W. J. Kissock. 1975. Effect of soaking and deep planting on vegetative propagation of Populus and Salix. Intl. Poplar Comm., 15th Session, Dec. 1-6, 1975. FAO: Rome, 13 pp.

Farmer, R. E. 1966. Rooting dormant cuttings of mature cottonwood. J. For. 64:196-197.

Farrar, J. L. 1977. Root initiation in cuttings of Populus alba L. Proc. North Amer. Poplar Council Meet., Sept. 6-9, 1977, Brockville, Ont., p. 16-1 to 16-5.

Fege, A. S. and H. M. Phipps. 1982. Effect of collection date and storage conditions on field performance of Populus hardwood cuttings. Proc. North Amer. Poplar Council Meeting, July 20-22, 1982, Rhinelander, WI (Abstract).

Food and Agriculture Organization of the United Nations. 1979. Poplars and willows. FAO Forestry Series No. 10, 320 p.

Haissig, B. E. 1974. Origins of adventitious roots. New Zeal. J. For. Sci. 4:299-310.

Hansen, E., L. Moore, D. Netzer, M. Ostry, H. Phipps, and J. Zavitkovski. 1982. Establishing intensively cultured hybrid poplar plantations for fuel and fiber. USDA For. Serv. Gen. Tech. Rep. NC-78, 24 p.

Hansen, E. A. and D. N. Tolsted. 1981. Effect of cutting diameter and stem or branch position on establishment of a difficult-to-root Populus alba hybrid. Can. J. For. Res. 11:723-727.

Hartmann, H. T. and D. E. Kester. 1975. Plant propagation: Principles and practices. Prentice-Hall, Inc., 662 pp.

Krinard, R. M. and W. K. Randall. 1979. Soaking aids survival of long, unrooted cottonwood cuttings. Tree Planter's Notes 30(3):16-18.

Lust, N. and M. Mohammady. 1973. Regeneration of coppice. Sylva Gandavensis 39, Research Centre of Silviculture, Management and Forest Policy of the State University, Ghent, Belgium. 28 pp.

Mattson, J. A. and E. S. Miyata. 1982. A time study of planting a short-rotation intensively cultured plantation. USDA For. Serv. Res. Note NC-278, 4 p.

McKnight, J. S. 1970. Planting cottonwood cuttings for timber production in the South. USDA For. Serv. Res. Pap. SO-60, 17 pp.

McKnight, J. S. and R. C. Biesterfeldt. 1968. Commercial cottonwood planting in the Southern United States. J. For. 66:670-675.

Ostry, M. E. and H. S. McNabb, Jr. 1982. Preventing blackstem damage to Populus hardwood cuttings. Proc. North Amer. Poplar Council Meeting, July 20-22, 1982, Rhinelander, WI. p. 36-43.

Petersen, L. A. and H. M. Phipps. 1976. Water soaking pretreatment improves rooting and early survival of hardwood cuttings of some Populus clones. Tree Planter's Notes 27(1): 12,22.

Phipps, H. M. and E. A. Hansen. 1983. Effect of soil moisture tension and pre-plant treatments on early growth of hybrid Populus hardwood cuttings. Can. J. For. Res. (In press).

Phipps, H. M., E. A. Hansen and A. S. Fege. 1983. Preplant soaking of dormant Populus hardwood cuttings. USDA For. Serv. Res. Report NC- (In press).

Phipps, H. M. and D. A. Netzer. 1981. The influence of collection time and storage temperature on Populus hardwood cutting development. Tree Planter's Notes 32(4):33-36.

Prairie Farm Rehabilitation Administration. 1979. Annual Report 1978 for tree nursery, Indian Head, Saskachewan. Mimeo.

Smith, N. G. and P. F. Wareing. 1972a. The distribution of latent root primordia in stems of Populus robusta, and factors affecting the emergence of preformed roots from cuttings. For. 45:197-209.

Smith, N. G. and P. F. Wareing. 1972b. Rooting of hardwood cuttings in relation to bud dormancy and the auxin content of excised stems. New Phytol. 71:63-80.

Swingle, C. F. 1929. A physiological study of rooting and callusing in apple and willow. J. Agr. Res. 39:81-128.

Venn, K. 1980. Winter vigor in Picea abies (L.) Karst. VII. Development of injury to seedlings during overwinter cold storage, a literature review. Medd. Norsk Inst. for Skogforskning 35:483-530.

Williams, R. D. and S. H. Hanks. 1976. Hardwood nurseryman's guide. USDA For. Serv. Agr. Handbook No. 473, 78 p.

SURVIVAL AND GROWTH OF TWO INTENSIVELY CULTURED JACK PINE PROVENANCES RAISED IN TUBEPAK AND JIFFY 7 CONTAINERS

J. Zavitkovski and Howard M. Phipps[1]

Abstract.--Container type, provenance, and spacing affect survival, height and d.b.h. growth, and biomass production of intensively cultured jack pine. The Lower Michigan provenance and Tubepak grown plants performed better than the local (Wisconsin) provenance and plants raised in Jiffy 7 pellets. At age 5, biomass of Tubepak plantings was more than 100% higher than that of Jiffy 7 plantings. Plantings of the Michigan provenance had 73% more biomass than those of the local source. The above-ground dry weight yield of the 1.0 x 0.3 m (3.3 x 1 ft) planting at age 5 (60.8 mt/ha (27 tons/acre)), approached yields expected or predicted for hybrid poplar plantations in the Lake States. And jack pine has several advantages over hybrid poplar as a source of biomass for energy: it can be harvested during any season of the year (most hybrid poplars can only be harvested during the dormant season), it can be harvested with stumps and roots (hybrid poplar stumps must be left so new coppice stand can develop), and heat of combustion of jack pine biomass is about 8% higher than that of hybrid poplar biomass.

The present study was designed to show that in suitable containers and under intensive culture, jack pine of a good provenance would grow very rapidly and produce large quantities of biomass. In a previous study (Zavitkovski and Dawson 1978), initial slow growth of jack pine tubelings was traced to the small size and rigid walls of the plastic container that restricted root development and seedling growth. At age 2, the average height of the tubelings was at least 1 year behind that of freely developing seedlings raised under less intensive cultural conditions (Jeffers and Nienstaedt 1973).

In this study we compared survival, and height and d.b.h. growth of two jack pine provenances, a local and a recommended Lower Michigan provenance (Jeffers and Jensen 1980) grown in two containers -- Jiffy 7 pellets and Tubepaks -- at three spacings.

The study was established in 1978 on the Harshaw Forestry Research Farm located about 10 miles west of Rhinelander, WI. The land of the farm is level and was used for about 50 years to grow potatoes. The Farm is operated by researchers at the Forestry Sciences Laboratory, Rhinelander, WI.

MATERIALS AND METHODS

Seed from the Lower Michigan provenance was collected in 1974 from Grand Traverse County, latitude 44.5°N and assigned number NC-7738. Seed from the Wisconsin provenance, number NC-8806, was collected in the winter of 1975/76 from Oneida County, latitude 45.75°N. All seed was kept in cold storage until the beginning of this study.

After a brief stratification, the germinating seed was planted in Jiffy 7 pellets and Tubepak containers[2/3/] filled with a 3:1:1

[1]Research Foresters, North Central Forest Experiment Station, Forestry Sciences Laboratory, Rhinelander, WI 54501

[2]The Jiffy 7, manufactured by Jiffy Products of America, is a compressed pellet of peat moss (with fertilizer) that expands upon soaking to form a container about 4 cm (1 3/4 inches) in diameter and 5 cm (2 inches) high (ca. 78 cm^3 or 5 cu in). A plastic net holds the container together. The Tubepak is a semitransparent plastic container that has several cavities each measuring 4 x 5 x 18 cm (1½ x 2 x 7 in) (ca. 266 cm^3 or 17 cu in). It is made up of two parts that can be separated to permit removal of the seedlings for transplanting.

mix of peat, vermiculite, and perlite. They were grown for 5 months (December 1, 1977 to April 30, 1978) in a greenhouse using standard treatment including frequent watering, application of balanced nutrient solution, and daylength extended to 16 hours with incandescent light.

In May 1978, we moved the seedlings into a shadehouse to harden them off and bring them into a dormant stage to ensure thay they would resume growth in the field. The treatment was only partly successful. Many of the seedlings did not set bud, remained succulent and had to be planted carefully to keep them in a vertical position.

At age 6 months, before outplanting, heights of the seedlings averaged:

Container	Grand Traverse, MI	Oneida, WI
	Mean (SD), cm	
Jiffy 7	18.4 (4.2)	17.5 (3.7)
Tubepak	19.4 (3.8)	19.6 (3.2)

Only heights of the Oneida County seedlings (17.5 vs 19.6) were significantly different (at the 5% level).

The seedlings were hand-planted in rows 1 m (3.3 ft) apart. Three spacings were achieved by planting seedlings 0.3 (73 seedlings/row), 0.6 (41 seedlings/row), and 1.0 m (25 seedlings/row) (1, 2, and 3.3 ft) within rows. Seven rows were planted for each of the 6 spacing-container combinations, for a total of 42 rows per provenance. Seedlings from the two sources were planted in blocks separated by a 4 m (13 ft) lane, and one border row was provided around the entire 0.3 ha (0.75 acre) study area. Soil is in the Padus series grading from a silt loam to a sandy loam with sand to gravelly sand subsoil.

The plantings were irrigated when the soil moisture tension reached - 0.5 bar as measured at the 15-30 cm (6-12 in) depth with tensiometers. They were fertilized annually with 112 kg/ha (100 lbs/acre) N applied in several applications through the irrigation system.

All live trees were counted at the end of each growing season. In the middle 3 rows of each spacing-container combination, height was measured every year from age 2. At ages 4 and 5, d.b.h. was measured on 10 systematically selected live trees/row.

---

[3]The use of trade, firm, or corporation names in this publication is for the information and convenience of the reader. Such does not constitute an official endorsement by the U.S. Department of Agriculture of any product or service to the exclusion of others thay may be suitable.

RESULTS AND DISCUSSION

All three main variables -- provenance, container type, and spacing -- strongly affected survival and height and d.b.h. growth. In most instances, differences between average values were consistent from 1 to 5 years.

Survival

Plants raised in Tubepak containers and the Michigan seed source had a higher survival than plants raised in Jiffy 7 pellets and the Wisconsin (local) seed source (Table 1). Most of the mortality occurred during the first year in the field and, generally, was low during the subsequent 4 years. Density effects on survival were not consistent -- overall survival at age 5 averaged 76, 71, and 77% in plantings spaced at 1.0 x 0.3, 1.0 x 0.6, and 1.0 x 1.0 m, respectively.

At age 5, the Michigan provenance raised in Tubepak containers had the highest survival -- 89% -- and the local provenance raised in the Jiffy 7 pellets had the lowest survival -- 61% (Table 1). In the previous study (Zavitkovski and Dawson 1978), the survival of the jack pine tubelings at age 4 ranged from 84 to 100%. In Minnesota, jack pine tubelings under field conditions had a 77% survival at age 2 and 65% at age 5 (Alm and Schantz-Hansen 1970, 1972). These tubelings were much shorter than our intensively cultured jack pine.

Height and d.b.h. growth

At the end of the greenhouse phase (6 months), seedlings raised in the Tubepak containers were taller than those in the Jiffy 7 pellets, but it was not yet clear which of the two sources might be better. The superiority of the Michigan source became evident at age 2 and significant at age 5 (Table 1).

At age 2, plants of the Michigan provenance were about 23% taller than those of the local provenance, and at age 5 they were about 4% taller. However, the height difference remained about the same -- 10 cm (4 in) -- as at age 2. The mean difference in height between plants raised in Tubepak containers and Jiffy 7 pellets was 29% at age 2 and 16% at age 5. However, the absolute height difference was 12½ cm (5 in) at age 2 and 35 cm (11 in) at age 5 in favor of the Tubepak plants. This shows that the effect of container type on height was greater than the effect of provenance through age 5.

Spacing effect on height growth, like that on survival, was inconsistent. The average maximum height of 280 cm (9.2 ft) was reached at age 5 in the Michigan planting spaced 1.0 x 0.3m(Table 1). The most uniform average heights -- from 232 to 253 cm (7.6 to 8.3 ft) -- were reached in the 1.0 x 1.0 m plantings of both provenances.

Table 1.--Survival, height, and dbh of 1- to 5-year-old intensively cultured jack pine

AGE	SURVIVAL (%)				HEIGHT (cm)[1/]				DBH (mm)[1/]			
	MICHIGAN		WISCONSIN		MICHIGAN		WISCONSIN		MICHIGAN		WISCONSIN	
	JIFFY 7	TUBEPAK	JIFFY 7	TUBEPAK	JIFFY 7	TUBEPAK	JIFFY 7	TUBEPAK	JIFFY 7	TUBEPAK	JIFFY 7	TUBEPAK
SPACING: 1.0 x 0.3 m (Initially 73 seedlings per row.)												
1	79	95	74	85								
2	77	94	67	83	48	65	40	49				
3	76	93	63	82	113	140	89	108				
4	74	93	63	78	182$_{c}$	212$_{a}$	149$_{d}$	172$_{b}$	12$_{b}$	17$_{a}$	7$_{c}$	10$_{bc}$
5	71	92	63	76	236$_{c}$ [3/]	280$_{a}$	210$_{d}$	256$_{b}$	22$_{b}$	26$_{a}$	17$_{c}$	20$_{bc}$
SD[2/]					37	29	36	38	8	8	6	6
SPACING: 1.0 x 0.6 m (Initially 41 seedlings per row.)												
1	70	96	82	91								
2	64	94	68	90	45	66	40	50				
3	64	93	63	89	92	126	87	123				
4	57	91	63	88	141$_{b}$	203$_{a}$	149$_{b}$	190$_{a}$	7$_{c}$	16$_{a}$	7$_{c}$	14$_{b}$
5	54	86	59	86	216$_{b}$	261$_{a}$	215$_{b}$	263$_{a}$	19$_{c}$	29$_{a}$	19$_{c}$	25$_{b}$
SD[2/]					46	35	33	28	9	9	7	5
SPACING: 1.0 x 1.0 m (Initially 25 seedlings per row.)												
1	82	95	69	90								
2	81	95	68	87	50	58	40	52				
3	78	95	66	87	108	125	95	120				
4	76	89	60	83	174$_{ab}$	191$_{a}$	149$_{b}$	184$_{a}$	12$_{ab}$	14$_{a}$	8$_{b}$	14$_{ab}$
5	75	89	60	83	242$_{ab}$	253$_{a}$	232$_{b}$	249$_{a}$	26$_{ab}$	28$_{a}$	22$_{b}$	26$_{ab}$
SD[2/]					40	45	30	33	10	10	7	8
ALL 3 SPACINGS POOLED												
1	77	95	75	89								
2	74	94	68	87	48	63	40	50				
3	73	94	64	86	104	130	90	117				
4	69	92	62	83	166	202	149	182	10	16	7	13
5	67	89	61	82	231	265	219	256	22	28	19	24

1/ To convert centimeters and milimeters into inches multiply by 0.394 and 0.0394, respectively.

2/ Standard deviation for age 5 of height and d.b.h. is based on 30 measurements, i.e., 10 per row in the middle 3 rows.

3/ At age 5, average heights and d.b.h.'s are not significantly different (at the 5% level) if followed by the same letter.

The effect of spacing on d.b.h. growth was essentially positive. This trend was clearly demonstrated in trees from the Wisconsin source but although it was present, it was not so obvious in trees from the Michigan source.

At age 5, the average height of the trees -- 210 to 280 cm (almost 7 to more than 9 ft) -- was substantially greater than that of the Tubeling jack pine -- 170 to 194 cm (5½ to 6½ ft) -- used in the previous study (Zavitkovski and Dawson 1978). Actually, the heights were within the range of the 6-year-old tubeling trees (247 to 277 cm or 8 to 9 ft).

Our plants grew equally well or better than intensively cultured jack pine in other studies. Three-year-old seedlings of the best Lower Michigan Peninsula provenance averaged 130 cm under nursery culture which included fertilization and irrigation (Canavera and Wright 1973). In our study, 3-year-old seedlings from the Michigan source raised in Tubepaks averaged 130 cm and in the 1.0 x 0.3 m planting averaged 140 cm (Table 1). In a provenance test at Rhinelander, 2-year-old plants of the best Lake States provenances, raised in Jiffy 7 pellets, averaged 50 cm in height (Jeffers and Nienstaedt 1973). Heights of our 2-year-old plants ranged from 40 to 63 cm.

In traditionally cultured plantations, jack pine grows more slowly and height at age 4 averages only about 112 cm in northern Wisconsin (Rudolph 1981); 83 cm in Vermont (Adams 1928); and from 54 to 60 cm in Michigan (Rudolf 1951). At age 5, height of field-planted jack pine tubelings averaged 76 cm in Minnesota (Alm and Schantz-Hansen 1972), bare root planted stock averaged 116 cm in Vermont (Adams 1928) and from 98 to 129 cm in Ontario (Logan 1966, Yeatman 1974).

The d.b.h. of our 5-year-old plants ranged from 18 to 30 mm (0.7 to 1.2 in) (Table 1), and was similar to the d.b.h. reached by 7-year-old trees -- 17 to 30 mm -- in the previous study (Zavitkovski and Dawson 1978). D.b.h. of field-planted jack pine ranged from 19 to 33 mm (0.7 to 1.3 in) in a 10-year-old plantation established with 1-0 stock in Lower Michigan (Rudolf 1951). Not only the d.b.h., but also the average height of these plants was similar to our 5-year-old, intensively cultured jack pine.

Aboveground tree biomass

We estimated total aboveground biomass (including needles) of our 4- and 5-year-old plantings by means of an equation developed for 6- and 7-year-old intensively cultured jack pine spaced at 0.6 x 0.6 m (2 x 2 ft) (Zavitkovski and Dawson 1978):

$$\ln \text{Aboveground biomass} = -6.5642 + 2.1891 \ln \text{d.b.h.}$$

In this equation, biomass is in kg, d.b.h. is in mm, $R^2 = 0.9411$, $sy.x = 0.2124$, and the correction factor is 1.0228. Stems, branches, and needles accounted for about 45, 29, and 26% of the total biomass, respectively.

Container and provenance effect on dry weight was greater and more variable than their effect on height and d.b.h. In general, biomass decreased as spacing increased (Table 2). Biomass of plantings established from seedlings grown in Tubepaks was from two to several times greater than that of plantings established from seedlings grown in Jiffy 7 containers. The most biomass was in the 1.0 x 0.3 m planting of the Michigan source raised in Tubepaks -- about 60.8 mt/ha at age 5 -- and the least was in the 1.0 x 1.0 m planting of the local source raised in the Jiffy 7 pellets -- about 8.2 mt/ha. Previous studies have demonstrated that total biomass differences between dense and open plantations gradually diminishe (Zavitkovski and Dawson 1978).

The highest total tree aboveground biomass achieved in this study - 60.8 mt/ha -- was about 10% higher than the maximum -- 56.8 mt/ha -- reached in the previous study (Zavitkovski and Dawson 1978) at age 7. This yield approaches mean annual biomass increments expected or predicted for various hybrid poplars. However, jack pine has three advantages over poplar: (1) it can be harvested with roots that may amount to about 20% of the aboveground biomass, i.e. about 12½ mt/ha at age 5; (2) it can be harvested at any time of the year whereas hybrid poplars must be harvested during the dormant season (Strong and Zavitkoski 1982) to ensure the best coppice regeneration; and (3) its heat of combustion is about 8% higher than that of hybrid poplar. Its main disadvantage is that it has to be replanted after each harvest, whereas poplars regenerate by coppicing. These points should be considered when deciding which species to use in energy plantations.

Container effect

The difference in growth between seedlings raised in the Tubepak and Jiffy 7 containers may be partly explained by the difference in container volume. The larger volume of the Tubepak would permit the development of a larger root system. However, some evidence suggests that the plastic net surrounding the Jiffy 7 container may deform or restrict the normal development of the root system of some tree species as they grow older. In the present study, the difference in height, d.b.h. and particularly total dry weight of Tubepak and Jiffy 7 plants appeared to be increasing through age 5 (Tables 1 and 2).

Table 2.--Preliminary estimates of above-ground tree biomass of 4- and 5-year old intensively cultured jack pine[1/] (In metric tons per hectare)[2/]

SPACING	AGE	MICHIGAN		WISCONSIN	
m	yrs.	JIFFY 7	TUBEPAK	JIFFY 7	TUBEPAK
1.0 x 0.3	4	11.9	25.3	3.6	7.4
	5	33.3	60.8	16.0	28.1
1.0 x 0.6	4	2.2	10.7	1.8	7.5
	5	10.0	36.2	10.3	25.5
1.0 x 1.0	4	3.3	4.9	1.4	4.3
	5	16.1	23.1	8.2	15.8

1/
2/ Stems, branches, and needles accounted for about 45, 29, and 26%, respectively. To convert metric tons per hectare into tons per acre multiply by 0.445.

After 2 years in the field, we found that poplar hybrid cuttings rooted in Jiffy 7 pellets were consistently shorter than those rooted in a similar container but without the plastic net coverings.[4/] An examination of the root systems of several poplar hybrid trees propagated in Jiffy 7 containers and grown for 6 months in pots in a greenhouse showed fewer long roots than those grown in pots without the container. Also, roots of the former plants tended to grow horizontally and to have a spiral configuration.

CONCLUSIONS

1. Results of the study indicate that selection of container type, provenance, and spacing is extremely important and may affect survival, height, d.b.h., and biomass of jack pine plantations for at least 5 years.
2. In the field, plants from the Michigan source and Tubepaks had a higher survival -- by 6½% for the source and 21% for the container at age 5 than those from the Wisconsin source and Jiffy 7 pellets.
3. The effect of container type on height showed up at age 6 months in the greenhouse, became significant at age 2 years in the field, and then remained about the same through age 5 -- about 22% in favor of the Tubepaks.
4. Provenance had no effect on height in the greenhouse. In the field, the difference reached about 20% in favor of the Michigan source at age 2 and then gradually decreased to 4% at age 5.
5. Container type and provenance had a greater effect on diameter than on height. At age 5, Tubepak plants had a 24% greater d.b.h. than Jiffy 7 plants, and the Michigan source had a 14% greater d.b.h. than the one from Wisconsin.
6. The greatest effect of the container type and provenance showed up in total biomass, which incorporates both height and d.b.h. differences. At age 5, biomass of the Tubepak plantings was 102% greater than that of Jiffy 7 plantings. Plantings of the Michigan source had 73% more biomass than those of the Wisconsin source.
7. From age 1 to 5, the densest plantings had the greatest biomass. At age 5, the overall averages were 35, 20, and 16 mt/ha in plantings spaced at 1.0 x 0.3, 1.0 x 0.6, and 1.0 x 1.0 m, respectively.
8. The highest aboveground yield of 60.8 mt/ha at age 5 approaches yields reached in hybrid poplar plantations. The advantages of jack pine over hybrid poplars are (1) it can be harvested at any time of the year; (2) it can be harvested with roots; and (3) its heat of combustion is about 8% higher.

4/ H. M. Phipps, unpublished data.

ACKNOWLEDGMENT

We thank Daniel A. Netzer for supervising the establishment of the plantation. The study was supported in part by the Department of Energy under an Interagency Agreement DE-AI-05-800R20763.

LITERATURE CITED

Adams, W. R., Jr. 1928. Studies in tolerance of New England trees. VIII. Effect of spacing in jack pine plantation. Vermont Agr. Exp. Sta. Bull. 282, 55 p.

Alm, A. A., and R. Schantz-Hansen. 1970. Planting pine tubelings in Minnesota. J. For. 68(6): 353-357.

Alm, A. A., and R. Schantz-Hansen. 1972. Five-year results from tubeling plantings in Minnesota. J. For. 70(10): 617-619.

Canavera, D. S., and J. W. Wright. 1973. A 4-year provenance test of jack pine. Michigan State U., Agric. Exp. Sta. Res. Pap. 204, 7 p.

Jeffers, Richard M., and Raymond A. Jensen. 1980. Twenty-year results of the Lake States jack pine seed source study. USDA For. Serv. Res. Pap. NC-181, 20 p.

Jeffers, Richard M., and Hans Nienstaedt. 1973. Precocious flowering and height growth of jack pine full-sib families. In: IUFRO Progeny Testing Proc., J.F. Kraus, ed., p. 19-27, Macon, Georgia.

Logan, K. T. 1966. Growth of tree seedlings as affected by light intensity. II. Red pine, white pine, jack pine, and eastern larch. Dep. For. Can., Publ. 1160.

Rudolf, Paul O. 1951. Stand density and the development of young jack pine. J. For. 49: 254-255.

Rudolph, Thomas D. 1981. Four-year height growth variation among and within S_o, S_1xS_1, and S_1 open-pollinated and S_2 inbred jack pine families. Can. J. For. Res. 11: 654-661.

Strong, Terry F., and J. Zavitkovski. 1982. Harvesting season affects regeneration and growth of Populus 'Tristis #1' coppice. In: 19th Annual Meeting of North American Poplar Council, Rhinelander, WI., Jerry Zavitkovski and Edward A. Hansen (eds.), Kansas State Univ. Press, Manhattan, KS., p. 103-112.

Yeatman, C. W. 1974. The jack pine genetics program at Petawawa Forest Experiment Station 1950-1970. Dep. Environ., Can. For. Serv. Publ. 1331.

Zavitkovski, J., and David H. Dawson. 1978. Structure and biomass production of 1- to 7-year-old intensively cultured jack pine plantations in Wisconsin. USDA For. Serv. Res. Pap. NC-157, 15 p.

MYCORRHIZAE OF POPLARS[1]

R. C. Schultz
J. G. Isebrands
P. P. Kormanik[2]

Abstract. Poplar hybrids, being screened for short-rotation intensive culture, can form ecto-, endo-, or ectendo-mycorrhizae or may be autotrophic. Different sections of the genus Populus tend to be selective in the type of mycorrhizae formed. Knowledge of which types are formed influences the kinds of propagule production, site preparation, and herbicide techniques that should be used in establishing poplar plantations.

INTRODUCTION

Since 1970, the North Central Forest Experiment Station at Rhinelander, Wisconsin, has been screening Populus clones on the basis of their growth potential for short-rotation intensive culture (SRIC). Specific studies have been conducted on the relationship between morphological and physiological variables and the quantity and quality of yield for selected clones. However, a better understanding of the physiological interactions in the root zone of SRIC poplars is needed to improve cultural practices and yields. One of the most important interactions in the root zone is the symbiosis between roots and fungi called mycorrhizae. This research was conducted to describe the importance of mycorrhizae to the establishment and growth of Populus trees.

With few exceptions, all plants in nature develop mycorrhizae to various degrees. Wilhelm (1966) states that, under field conditions, plants do not, strictly speaking, have roots, but rather, mycorrhizae. Mycorrhizae have been shown to improve the growth of trees through their influence on nutrient and water uptake, disease resistance, high temperature tolerance, and hormone interactions. However, most of the major research efforts reported in the literature to date have been on nutrient-uptake interactions. The two major types of mycorrhizae most frequently encountered are "ectomycorrhizae" and "endomycorrhizae." A third type, "ectendomycorrhizae," is less frequently encountered and poorly understood.

Ectomycorrhizae

Ectomycorrhizal infection is initiated from spores or hyphae (collectively referred to as "propagules") of certain fungal symbionts in the rhizosphere of feeder roots. These propagules are stimulated by root exudates and grow vegetatively over the feeder-root surface, forming the external fungal mantle. After mantle development, hyphae develop intercellularly in the root cortex, forming the "Hartig-net," which may completely replace the middle lamellae between cortical cells. This Hartig-net is the major diagnostic feature of ectomycorrhizae. Ectomycorrhizae may appear either as simple unforked roots, bifurcate roots, multiforked

[1]Journal Paper No. J-10984 of the Iowa Agriculture and Home Economics Experiment Station, Ames, Iowa. Projects No. 2523 and 2524.

[2]Authors are Professor, Forestry Department, Iowa State University, Ames, Iowa 50011; Wood Scientist, Forestry Sciences Laboratory, North Central Forest Experiment Station, Rhinelander, Wisconsin 54501; and Principal Silviculturalist, Institute for Mycorrhizal Research and Development (IMRD), Southeastern Forest Experiment Station, Athens, Georgia 30602.

roots, or even nodular-like roots that are readily visible to the naked eye. The visible structures are commonly referred to as "short roots." Each individual short root, regardless of branching pattern, is an ectomycorrhiza. Individual hypha, multiple hyphae, or rhizomorphs may radiate into the soil from the fungus mantles on short roots and eventually unite with the base of fruiting bodies of the fungus (Marx, 1975; Smith, 1980).

It is estimated that more than 2100 species of ectomycorrhizal fungi exist on trees in North America. Most fungi that form ectomycorrhizae with forest trees are Basidiomycetes that produce mushrooms or puffballs as reproductive structures. However, certain of the Ascomycetes, such as truffles, also are symbiotic. The fruiting bodies of these fungi produce millions of spores that are widely disseminated by wind and water. Moreover, most ectomycorrhizal fungi are dependent on their tree hosts for essential carbohydrates, amino acids, vitamins, etc., needed to complete their life cycle. Thus, ectomycorrhizal development with a host is usually a prerequisite for fruiting-body production by these fungi.

Under normal forest conditions, many species of fungi may be involved in the ectomycorrhizal associations of a forest, a single tree species, an individual tree, or even a small segment of lateral root. Indeed, as many as three species of fungi have been isolated from an individual ectomycorrhiza (Marx, 1975). A single species of fungus may also enter into ectomycorrhizal association with numerous tree species. Some of the fungi may be rather host specific, but little work has been done on this phenomenon.

Ectomycorrhizae occur naturally on many of the important forest tree species of the world. All members of the gymnosperm family Pinaceae are ectomycorrhizal; i.e., Pinus (pine), Picea (spruce), Abies (fir), Larix (larch), Tsuga (hemlock), and Pseudotsuga (Douglas-fir), as well as certain angiosperms such as Salix (willow), Populus (aspen), Carya (hickory and pecan), Quercus (oak), and Fagus (beech).

Endomycorrhizae

Endomycorrhizal fungi, commonly referred to as the "vesicular-arbuscular" fungi, are the most widespread and important root symbionts. They are not restricted to specific groups of plants, but occur in practically all families of angiosperms, gymnosperms, and many pteridophytes and byrophytes. Most of the economically important grain and forage crops, as well as the major berry crops and fruit and nut trees, normally form endomycorrhizae. Many of our most important forest trees, such as Liquidambar (sweetgum), Platanus (sycamore), Ulmus (elm), Juglans (walnut), Fraxinus (ash), Liriodendron (yellow poplar), and Populus (cottonwood), form endomycorrhizae. Although endomycorrhizal fungi can form a loose network of hyphae on feeder-root surfaces, they do not develop the dense fungal mantle found on the ectomycorrhizae. Instead, endomycorrhizal fungi form large, conspicuous, thick-walled spores on the root surfaces, in the rhizosphere, and sometimes in feeder-root tissues. Endomycorrhizal fungal hyphae penetrate the cell walls of the epidermis and subsequently grow into the cortical cells of the root. Once in the cortical cells, these infective hyphae may develop specialized absorbing or nutrient-exchanging structures called "arbuscules." Arbuscules consist of dense clusters of very fine dichotomously branched filaments that may occupy the entire lumen of the cell. Vesicles develop later, generally in the middle and outer cortex, and appear as terminal swellings either within or between cells. No external morphological changes occur in roots infected with endomycorrhizal fungi, although with some hosts, a yellow or brown color in the roots has been reported. Endomycorrhizal fungi rarely invade meristematic tissue. Many conflicting opinions have been expressed about the functions of the arbuscules. Generally, vesicles are regarded as temporary storage organs for the fungus, and arbuscules as the exchange sites between the fungus and the host cell.

The fungi that form endomycorrhizae are mainly Phycomycetes. They do not produce large, above-ground fruiting bodies or wind-disseminated spores as most ectomycorrhizal fungi do. Some of them produce large azygospores and chlamydospores on or in the roots, whereas others produce large sporocarps (5 to 10 mm diam.) containing many spores. Spread of of these fungi in soils is by root contact, moving water, insects, or animals. In the absence of a host, the spores of these fungi are still able to survive in the soil for many years. As with ectomycorrhizal fungus spores, endomycorrhizal spores apparently are stimulated to germinate by root exudates in the rhizosphere.

Ectendomycorrhizae

Ectendomycorrhizae have some of the features of both ecto- and endo-mycorrhizae. They have a limited occurrence and, with regard to forest trees, are found primarily on roots of ectomycorrhizal trees. However,

very little is known about the species of fungi involved or their importance to the growth of trees because little research has been done on them.

Poplar Mycorrhizae

Relatively little is known about poplar mycorrhizae. Walker (1980) made a detailed survey of the literature concerning the mycorrhizae of Populus. He listed all assumed or proven mycorrhizal fungal associates with Populus species (Table 1). Twenty poplar species were shown to be mycorrhizal and all or any of the three major types of mycorrhizae; ecto-, endo-, and/or ectendo-mycorrhizae may be present. Eight poplar species are also shown to be capable of autotrophic growth without mycorrhizae. Poplars can be mycotrophic or autotrophic, depending on age and environmental conditions (Dominik, 1956, 1958). This ability is seen as an advantage for pioneer species that usually become established on drastically altered sites where mycorrhizal fungal inoculum may not be readily available.

Very little work has been done on the ecology and physiology of mycorrhizal poplars. However, Walker and McNabb (1983) recently assessed growth differences and mycorrhizal conditions of seven clones of poplar that were grown from rooted cuttings in five different unsterilized Iowa soils for 1 year in a greenhouse. Four of the soils were from central Iowa, and the fifth was from northeastern Iowa. Two of the soils were from woodland sites where Populus grandidentata Michx. was the major tree species, and one soil from an oak-hickory-elm woodland where Populus spp. were absent. The other two soils were from agricultural sites (corn-soybean fields). One of these soils had received frequent fertilizer and herbicide applications while the other had never been treated with agricultural chemicals. The seven clones used are given in Table 2. All three major types of mycorrhiza were found in the genus Populus. Their results also suggest that there may be differences in mycorrhizal development between the different sections of Populus. NC-5260 (North Central Forest Experiment Station (NC) number 5260), of the Tacamahaca group, seemed able to form any of the three types of mycorrhizae. NC-5339, of the Leuce group formed ecto- and ectendo-mycorrhizae, but formed only a few endomycorrhizae. The P. euramericana clones, of the Aigeiros group, formed many endomycorrhizae but did not form either of the other two mycorrhizae.

In another study, Walker et al., (1982) planted four clones of hybrid poplars at two locations in central Iowa to investigate the development of mycorrhizae over time and the changes in their populations in the soil. The four clones used were four of the same ones used in the previous study; namely, NC-5260, NC-5323, NC-5326, NC-5339. One of the sites was a sandy terrace near the Des Moines River, well above flood level. This site was occupied by poorly growing white ash (Fraxinus americana L.). The second site was meadow land on a silt-loam soil in the floodplain of a small stream that occasionally flooded. Vegetation on this site consisted of a mixture of grasses, smooth brome (Bromus inermis Leyss.), and foxtail (Setaria spp.). Both sites were tilled, and then rooted cuttings were planted. During the growing season, cuttings were periodically excavated, and plant root and rhizosphere soil samples collected.

A total of 15 species of endomycorrhizae were found on the two sites (Table 3). Ten of those were found at the first site, and 12 at the second site. This diversity was greater than the 3 to 5 species per site that have been commonly reported in the literature. Walker et al. (1982) suggest that these numbers were not unrealistic, but, rather, the result of more intensive and careful sampling. The spatial distribution of species spores were usually unevenly grouped over the site. This grouping was thought to be related to association of fungi to previous vegetation distribution. No differences were found in spore numbers related to clones, suggesting that clones either had no effect or had similar effects on spore production. There was little mycorrhizal development on the poplar roots despite large numbers of spores in the soil. This supports the idea that the trees had little influence on the spore populations. Spore numbers in the soil tended to be least in spring and greatest in late summer and early autumn. These differences might be directly or indirectly related to soil moisture conditions. Plowing and herbicide application could depress spore production. Walker et al. (1982) concluded that, although there are large numbers of spores available on many sites, a knowledge of the fungal species and their diversity, distribution, and population levels would be useful in determining site preparation and planting strategies for poplar plantations.

Table 1. Mycorrhizal status of poplars surveyed for mycorrhizae by Walker (1980). (+ = present; - = absent; blank = no data.)

Genus section and poplar species[a]	ect[b]	ecten[b]	end[b]	aut[b]
Leuce				
P. alba	+		+	+
P. canescens	+			
Aigeiros x Leuce				
P. nigra x *alba*	-		+	-
Aigeros				
P. deltoides	+		+	+
P. x *euramericana*	+	+	+	+
P. fremontii S. Wats.	+		-	
P. x *marilandica*	+		+	-
P. nigra	+		+	-
P. regenerata Henry	+		-	-
Tacamahaca x Aigeiros				
P. x *berolinensis*	+		+	-
(Tacamahaca x Aigeiros) x Aigeiros				
P. x *generosa* Henry x *nigra*	+		+	
Tacamahaca				
P. angustifolia	+			
P. balsamifera	+			
P. candicans Aiton	+		-	-
P. trichocarpa	+			
Leucoides				
P. heterophylla L.	-		-	+
Tremulae				
P. grandidentata Michx	+		-	
P. tremula	+	+	+	-
P. tremuloides	+		+	
Tremula x Aigeiros				
P. tremula x *P.* x *euramericana*	+		-	-

[a] Includes varieties and subspecies.

[b] ect = ectomycorrhizal; ecten = ectendomycorrhizal; end = endomycorrhizal; aut = autotrophic.

Table 2. Overall mean mycorrhizal colonization levels for seven poplar clones grown for a year in a greenhouse in five Iowan soils. Minimum = 0, maximum = 3. Endo = endomycorrhiza, Ecto = ectomycorrhiza, Ecten = ectendomycorrhiza (Walker and McNabb, 1983).

Clone	Parentage of clone	Genus section	Endo	Thin-mantled Ecto	Ecten
NC-5260	P. tristis x P. balsamifera	Tacamahaca	2.12	0.08	0.36
NC-5323	P. x euramericana	Aigeiros	2.04	0	0
NC-5326	P. x euramericana	Aigeiros	1.80	0	0
NC-5328	P. x euramericana	Aigeiros	1.96	0	0
NC-5377	P. x euramericana	Aigeiros	1.80	0	0
NC-5339	P. alba x P. grandidentata	Leuce x Tremulae	0.24**[a]	0.48	0.44

[a]**Significantly lower than others in the same column (p = 0.01).

In this paper, we also report the results of a study on the mycorrhizal condition and growth of two SRIC poplar clones in the establishment year. The objective of this study was to determine whether two diverse Populus hybrids become ecto- or endo-mycorrhizal, or remain autotrophic when grown in soils inoculated with an ectomycorrhizal or endomycorrhizal fungus or with natural inoculum.

METHODS

The study was conducted at the North Central Forest Experiment Station's Harshaw Experimental Farm near Rhinelander, Wisconsin, during the summer of 1980. The two Populus clones used in the study were Populus Tristis Fisch. x P. balsamifera L. cv. 'Tristis #1' (NC-5260) and Populus euramericana (Dode) Guinier cv. Eugenii (NC-5326). The hardwood cuttings used for the study were collected from a cutting orchard at the farm and were approximately 25 cm long.

The mycorrhizal fungi used were produced at the IMRD. The ectomycorrhizal fungus was Pisolithus tinctorius (PT) grown in pure culture by the techniques of Marx and Bryan (1975). The endomycorrhizal fungus was Glomus fasiculatus (GF) produced by growing the fungus in sorghum (Sorghum vulgare (Stapf.) Haines var. roxburghii) pot cultures. The soil and roots of these pot cultures were

Table 3. Species of endomycorrhizae found in surveys of soil collections made at two field sites in central Iowa. (Walker and McNabb, 1983b.)

Fungal species on the sandy terrace	Fungal species on the silt-loam flood plain soil.
ACAULOSPORA spp.	
A. scrobiculata Trappe	A. scrobilculata
A. spinosa Walker & Trappe sp. ined.	A. spinosa
	A. trappei Ames & Linderman
GIGASPORA spp.	
Gi. calospora (Nicol. & Gerd.) Gerd. & Trappe	Gi. calospora
Gi. gilmorei Trappe & Gerdmann	Gi. gilmorei
Gi. rosea Nicolson & Schenk	
Gi. heterogama (Nicol. & Gerd.) Gerd. & Trappe	
GLOMUS spp.	
	Gl. albidus Walker & Rhodes sp. ined.
Gl. constrictus Trappe	
	Gl. epigaeus Daniels & Trappe
Gl. fasciculatus (Thaxter sensu Gerd.) Gerd. & Trappe	Gl. fasciculatus
Gl. geosporus (Nicol. & Gerd) Walker stat. ined.	Gl. geosporus[a]
	Gl. microcarpus Tul. & Tul.
Gl. mosseae (Nicol. & Gerd.) Gerd. & Trappe	Gl. mosseae
	Gl. occultus sp. ined.

[a] = Glomus macrocarpus var. geosporus (Nicolson & Gerdemann) Gerdemann & Trappe.

used as inoculum. The natural inoculum consisted of unidentified fungal symbionts contained in the unfumigated soil from the farm. The soil was a sandy loam with the following chemical analysis: 35mg/l Bray 1 extractable P, 237mg/l total P, 323mg/l total Kjeldahl nitrogen, 14mg/l extractable NO_3-N, 68mg/l K, 160mg/l Ca, 619mg/l, Al, 71mg/l Fe, a pH of 5.3, and 1.04% organic matter. The soil was fumigated with methyl bromide (Dowfume MC-2, Dow Chemical Co., Midland, MI 48604)[3] at a rate of 450g per 12m2 of soil surface (15cm deep).

The study was conducted in 1m x 1m x 1m wooden boxes similar to those used in numerous previous studies (Kormanik et al., 1981, 1982; Schultz et al., 1981, 1982). The bottoms of the boxes were filled with approximately 15cm of coarse gravel to facilitate drainage.

The study as a 2x4 factorial with 3 replications set up as a split plot in a randomized complete-block design. Whole-plot treatments consisted of either fumigated or unfumigated soils. Within the fumigated soils, there were three treatments. One was inoculated with PT at the rate of 1 liter per box (FPT), one was inoculated with GF at the rate of 1 liter per box (FGF), and one was left uninoculated (FC) as a control. The unfumigated soil (UF), with its natural inoculum, was the fourth treatment. Inoculum was mixed into the top 20cm of soil to allow contact with the full length of the cutting.

Soil pH was adjusted to 6.0 by adding hydrated lime ($Ca(OH)_2$) at the rate of 183g per box. No phosphorus or potassium fertilizer was added because low phospohrus was desired and potassium levels were sufficient for tree growth. A total of 1680kg/ha of NH_4NO_3 was added at eight equally spaced intervals throughout the study (21g/box, per addition).

Ten cuttings of each clone were planted in two adjacent rows in each box. Clones (subplots) were randomly assigned to the two sets of rows in each box. In the FPT treatment, five Jack pine (Pinus banksiana L.) were also planted to test the viability of the PT inoculum. PT is known to readily infect pine.

Growth responses to the treatments were measured twice during the study. The first measurement was done August 15, 1980. At that time, height, diameter, number of leaves, and leaf area were measured. The study was harvested October 15, 1980. In addition to these measurements, dry weights of the leaves, stems, cuttings, and roots were collected at this time. Ten percent of the fine feeder roots of each cutting were collected for mycorrhizal analysis. The endomycorrhizal roots were stained and analyzed according to a method of Kormanik et al. (1980). Ectomycorrhizal assays were made according to a method of Dr. Donald Marx of the IMRD (pers. commun.)

The data were analyzed by analysis of variance. Significant treatment differences were identified by use of the following orthogonal contrasts: 1) unfumigated vs. all the fumigated, 2) the fumigated control vs. fumigated inoculated, and 3) ectomycorrhizal vs. the endomycorrhizal treatment.

RESULTS AND DISCUSSION

Treatment Responses

There were no height growth differences among treatments at either of the two measurement dates (Table 4). It is possible that the large carbohydrate reserve in the cuttings may have been responsible for the lack of response. A two or more year study probably would be necessary to describe these treatment differences. On the other hand, it is possible that competition resulting from the close spacing of the cuttings in the boxes resulted in the similar height-growth responses among all treatments. Preferential allocation of photosynthates to stem elongation reduced the carbohydrates available for biomass production and diameter growth in some treatments.

There were no differences among treatments in the August measurement of cutting diameters (Table 4). By the middle of October, however, the cuttings growing in the UF soil had a significantly smaller diameter than those growing in any of the fumigated treatments (Table 5). These differences may be the result of a greater and more diverse

[3] Use of trade names is for convenience of the reader and does not constitute an endorsement by the USDA Forest Service.

Table 4. First season growth data for Tristis (NC-5260) and Eugenei (NC-5326) cuttings rooted under the following soil treatments: 1) fumigated soils that were a] inoculated with an endomycorrhizal fungus (FEN), or b] inoculated with an ectomycorrhizal fungus (FEC), or c] uninoculated (FC); or, 2) unfumigated soils with natural inoculum.

	Height (m)	Diameter (cm)	Number of leaves	Leaf area (cm^2)	Height (m)	Diameter (cm)
Clone						
NC-5260	0.88	0.86	45	5867	0.88	0.90
NC-5326	0.74	0.73	39	5674	0.92	0.95
Treatment						
UF	0.80	0.78	33	5474	0.86	0.88
FC	0.83	0.82	46	5918	0.94	0.96
FGF	0.81	0.81	41	5734	0.90	0.95
FPT	0.79	0.79	47	5958	0.89	0.92
Significance[a]						
Clone	**	**	**	--	--	*
Treatment	--	--	**	--	--	*
Contrasts[b]						
UF vs. all	--	--	*	*	--	*
FC vs. FEN, FEC	--	--	--	--	--	--
FEN vs. FEC	--	--	*	--	--	--

[a] Significant F values; **(.01); *(.05).

[b] Orthogonal contrasts; **=.01; *=.05.

24

Table 5. October biomass for Tristis (NC-5260) and Eugenei (NC-5326) cuttings rooted under the following soil treatments: 1) fumigated soils that were a] inoculated with an endomycorrhizal fungus (FEN), b] inoculated with an ectomycorrhizal fungus (FEC), or c] uninoculated (FC); or, 2) unfumigated soils with natural inoculum (UF).

	Hardwood Cutting Dry Weight (g)	New Stem Material Dry Weight (g)	Root Dry Weight (g)	Total Dry Weight Minus Leaf Weights (g)
Clone				
NC-5260	11.8	16.4	11.3	39.5
NC-5326	10.2	18.4	7.4	35.2
Treatment				
UF	10.8	14.9	8.7	34.1
FC	11.2	18.9	9.5	39.8
FGF	10.7	16.7	8.7	35.5
FPT	11.4	18.4	10.3	40.0
Significance[a]				
Clone	*	--	*	*
Treatment	--	*	*	*
Contrasts[b]				
UF vs. all	--	*	*	*
FC vs. FGF, FPT	--	*	--	--
FGF vs. FPT	--	*	*	*

[a]Significant F values; * = .05.

[b]Orthogonal comparisons; * = .05.

population of microorganisms in the UF soil, which put a greater symbiotic and pathological demand on the cuttings. There may also have been a competition effect from the weeds growing in the boxes. A similar response was observed for stem and root dry weights. Fumigation increased growth by 8 to 30%. The FGF treatment produced the second smallest trees, and there was little difference between the FPT- and FC-treatment trees. This result is evidence that the ectomycorrhizal development had no biological impact on the trees. As seen in other studies, smaller trees for the mycorrhizal treatments are the common occurrence under moderate to high phosphorus fertility. We believe this phenomenon is due to the preferential reallocation of photosynthates from the tops to the roots during the establishment of the mycorrhizal symbiosis.

Clonal Responses

'Tristis' grew rapidly early in the season, whereas 'Eugenei' put on extensive growth later in the growing season. At the August 15th measurement date, Tristis had put on significantly more height and diameter growth than Eugenei. However, by October 15th, Eugenei had equalled and surpassed the height growth and put on significantly more diameter growth than Tristis. For the most part, Tristis had put on all its growth by August 15, although there was a small amount of growth after that date.

Eugenei's growth continued over the whole growing season. When compared with Tristis, it retained its leaves for a much longer time. Although Tristis had significantly more leaves than Eugenei on August 15th, there was no difference in the total leaf area between the two clones because Eugenei's leaves were larger. By October 15th, Tristis had shed all its leaves while Eugenei still retained some near the top of the shoot. The parents of Tristis come from more northerly latitudes than Eugenei. Perhaps this is why Tristis is more sensitive to the early shortening of the seasonal photoperiod.

In terms of total biomass response, Tristis outgrew Eugenei (Table 5). Although the hardwood cutting weights at the end of the study were slightly heavier for Tristis, there was no difference in new stem growth produced on the cuttings. Leaf dry-weight comparisons could not be made because of our sample dates, but it seems likely that there was little difference in total mass of leaves produced by either clone. The major difference between clones in biomass occurred in root growth. The average Tristis tree produced almost 4g more root dry weight than did Eugenei. This response is of special interest when comparing the mycorrhizal responses of the two clones during the establishment year.

Mycorrhizal Responses

Eugenei trees produced more ecto- and endo-mycorrhizae than did Tristis (Table 6). For example, Eugenei had 63% of its fine roots infected in the FGF treatment and 52% in the UF treatment. This infection compares with 23% and 39% respectively, for Tristis. The observed infections suggest that Eugenei had a greater affinity for GF than for the native fungi in the UF treatment, whereas the reverse is the case for Tristis. The larger root system of Tristis also suggests that this clone exploited the soil profile more completely and therefore did not gain the same advantages from the mycorrhizal symbiosis than did Eugenei with its smaller root system. The ectomycorrhizal response of the two clones was not as clear. Upon close examination, only one site of ectomycorrhizal infection was found on any of the root samples. Fifty-seven percent of the Eugenei trees had one infection site, compared with 43% of the Tristis trees. Even for the ectomycorrhizal case, Eugenei had a greater percentage of trees infected than did Tristis. It seems that the minimal ectomycorrhizal infection had no biologically significant impact on the cuttings. However, ectomycorrhizal plants were generally 10 to 15% heavier than were endomycorrhizal plants. This growth difference probably is not the result of PT stimulation, but, rather, a lack of response to the symbiosis.

The results of this study are similar to those found in other experiments. Both clones will form endomycorrhizae, but both also seem to be capable of autotrophic growth. It seems that, under the phosphorus levels of this study (35mg/l Bray 1 extractable P), the trees do not form many mycorrhizae. However, at similar phosphorus levels, many other species do form extensive mycorrhizal root systems (Schultz et al., 1982). Before it can be stated that these clones are definitely capable of autotrophic growth, growth comparisons at different phosphorus levels must be made. Although neither clone showed much development of ectomycorrhizae with PT, the literature suggests that Tristis may have a greater selectivity for ectomycorrhizal development than does Eugenei.

Table 6. Mycorrhizal development in Tristis (NC-5260) and Eugenei (NC-5326) cuttings rotted in unfumigated soils with natural inoculum or fumigated soils inoculated with endo- or ecto-mycorrhizal fungi.

	% of Roots Infected			% of Trees with 1 infection site
	Unfumigated		Fumigated	
Clone	Endo	Ecto	Endo	Fumigated-Ecto
NC-5260	39	0	23	43
NC-5326	52	0	63	57

CONCLUSIONS

Populus hybrids show extensive selectivity in mycorrhizal formation. This selectivity should be identified for the most important clones available so that proper inoculum can be used in producing propagules. In addition, cultural practices, such as site preparation and weed control with herbicides, can influence the available inoculum on a planting site. Although some hybrids seem to show autotrophic growth without mycorrhizal development at relatively low available soil phosphorus levels, the potential for mycorrhizal formation should be established for all hybrids.

ACKNOWLEDGMENT

The authors thank Marynell Redman and Paul Ehlers for their technical support on the study at the Harshaw farm.

LITERATURE CITED

Dominik, T. 1956. Projekt nowego podizialu mikoryz ektotroficiznych oparty na cechach morfologiczno-anatomicznych. (Tentative proposal for a new classification scheme of ectotrophic mycorrhizae established on morphological and anatomical characteristics.) Rocz. Nauk Lesn. 14:223-245. (English translation published by NSF and USDA OTS 60-21383. 1962).

Dominik, T. 1958. Studium nad miktrofizmen rodzaju Populus. (Study on mycotrophy of the genus Populus). Badawczy Lesn. Prace 1958. 181:117-172. (English translation in Study on mycotrophy of forest trees. National Science Foundation OTS 60-21227. 1964.)

Kormanik, P.P., W.C. Bryan, and R.C. Schultz. 1980. Procedure and equipment for staining large numbers of root samples for endomycorrhizal assay. Can. J. Microbiol. 26:536-538.

Kormanik, P.P., W.C. Bryan, and R.C. Schultz. 1981. Effects of three vesicular-arbuscular mycorrhizal fungi on sweetgum seedlings from nine mother trees. For. Sci. 27:327-335.

Kormanik, P.P., W.C. Bryan, and R.C. Schultz. 1982. The influences of vesicular-arbuscular mycorrhizae on growth and development of eight hardwood tree species. For. Sci. 28:531-539.

Marx, D.H. 1975. Mycorrhizae and establishment of trees on strip-mined land. Ohio J. Sci. 75:288-297.

Marx, D.H. and W.C. Bryan. 1975. Growth and ectomycorrhizal development of loblolly pine seedlings in fumigated soil infected with fungal symbionts. For. Sci. 21: 245-254.

Schultz, R.C., P.P. Kormanik, and W.C. Bryan. 1981. Effects of fertilization and vesicular-arbuscular mycorrhizal inoculation on growth of hardwood seedlings. Soil Sci. Soc. Am. J. 45:961-965.

Schultz, R.C. and P.P. Kormanik. 1982. Vesicular-arbuscular mycorrhizae and soil fertility influence mineral concentrations in seedlings of eight hardwood species. Can. J. For. Res. 12:829-834.

Smith, S.E. 1980. Mycorrhizas of autotrophic higher plants. Biol. Rev. 55:475-510.

Walker, C. 1980. Hybrid poplar mycorrhizae and endogenous spores in Iowa. Unpublished Ph.D. dissertation. Iowa State University, Ames, Iowa. Available from: University Microfilms, Ann Arbor, MI Order #80-10265.

Walker, C., C.W. Mize, and H.S. McNabb, Jr. 1982. Populations of endogonaceous fungi at two locations in Central Iowa. Can. J. Bot. 60:2518-2529.

Walker, C. and H.S. McNabb, Jr. 1983. Mycorrhizae and associated fungal spores in seven hybrid poplars potted in five Iowan soils. Can. J. Bot. (in press).

Wilhelm, S. 1966. Chemical treatments and inoculum potential of soils. Annu. Rev. Phytopathol. 4:53-78.

EFFECT OF ALNUS GLUTINOSA ON HYBRID POPULUS GROWTH AND SOIL NITROGEN CONCENTRATION IN A MIXED PLANTATION

Jeffrey O. Dawson and Edward A. Hansen[1]

Abstract.--Height growth of hybrid Populus and soil nitrogen concentration around Alnus glutinosa stems differed significantly both spatially and with the Alnus/Populus mixture in a short-rotation intensively cultured mixed planting. Populus height growth comparable to that obtained from optimal rates of ammonium nitrate fertilization occurred where Alnus rows were directly adjacent to Populus rows and where Alnus comprised about 66% of the mix. Soil nitrogen concentration around Alnus was greatest where Populus rows were directly adjacent to Alnus rows. Results are consistent with speculation that stress on young Alnus induced by competition from more rapidly growing Populus resulted in rapid accretion of nitrogen in soil.

Poplar (Populus) plantations under intensive cultural conditions use large quantities of nitrogen. Aboveground components of young poplar plantations may take up as much as 90 kg/ha/yr (Hansen and Baker 1979). The possibility of using nitrogen-fixing trees to supply nitrogen has been extensively discussed (McIntyre and Jeffries 1932, Finn 1953, Red'ko 1958, Tarrant 1961, Dale 1963, DeBell and Radwan 1979, Gordon and Dawson 1979). Among the most intensively studied silvicultural systems that take advantage of nitrogen-fixing trees are mixed plantations of alders (Alnus) and hybrid poplars (Tarrant and Trappe 1971, DeBell 1975). Both alders and poplars have wood properties acceptable for chip and fiber products.

Published results by Zavitkovski and others (1979) show that height growth of trees incapable of symbiotic N_2 fixation decreases with distance from N_2-fixers for a number of species. Therefore, the spacing of N_2-fixing nurse trees in relation to associated trees needs to be considered if mixed plantations are to be efficient.

Another consideration when designing mixed plantations is the amount of N supplied by the N_2-fixers compared with the N demand of associated plants. Some of the probable factors affecting N supply by N_2-fixers to a mixed plantation are the percentage of N_2-fixers in the mix, the N_2-fixation rate, and the availability of N to the associated trees.

It is well documented that trees incapable of N_2 fixation usually show increased growth when mixed with N_2-fixers. Height and diameter growth of Douglas-fir (Pseudotsuga menziesii (Mirb.) Franco) were greater in plantations containing 59 percent red alder (Alnus rubra Bong.) than in pure plantations (Tarrant 1961, Miller and Murray 1978). In a 2-year coppice rotation, height and diameter growth of black cottonwood (Populus trichocarpa Torr. & Gray) were greater in stands containing 50 percent red alder than in pure stands (DeBell and Radwan 1979). Total yield of the mixed planting was about 50 percent greater than that of either species planted alone. Heights of several conifer and hardwood species (including Populus) increased from 4 to 50 percent when European black alder (Alnus glutinosa (L.) Gaertn.) was interplanted as a 50-percent mix (Dale 1963, Plass 1977). An underplanting of

[1]The authors are, respectively, Associate Professor, Department of Forestry, University of Illinois, Urbana, IL 61801 and Project Leader, North Central Forest Experiment Station, Forestry Sciences Laboratory, Rhinelander WI 54501.

European black alder accelerated both height and diameter growth of Populus (Van der Meiden 1961). These studies demonstrate that Populus will grow faster when planted with Alnus than when planted without, and that in some cases total yield is increased. However, the percentage of a N_2-fixer in mixed plantings necessary to promote optimal growth of an associated species has not been addressed.

In our studies, the influence of Alnus and hybrid Populus mixture on Populus height growth and soil N concentration around Alnus were investigated over a range of mixtures in a short-rotation intensively cultured plantation at Rhinelander, Wisconsin (Hansen and Dawson 1982, Dawson and others 1983). Results of these studies are summarized in this report.

METHODS

A 30 x 30 m plot at the Harshaw Forestry Research of the U.S. Forest Service, North Central Experiment Station, near Rhinelander, Wisconsin was planted in May of 1977. Planting stock consisted of 1-year-old, bare-root seedlings of an unknown seed source of A. glutinosa from a commercial nursery and greenwood tip cuttings of Populus rooted the previous fall in a "Jiffy-7" peat pellets. The Populus consisted of an inadvertent mixture of two hybrid clones: P. betulifolia x P. trichocarpa Torr. & Gray and a Populus clone of indeterminate origin. The trees were spaced at 1.2 x 1.2 m in 26 rows with 26 trees per row. Each row was planted with either alder or poplar. The mix of taxons graded from four consecutive poplar rows on one side of the plot through increasing frequency of alder rows to four consecutive rows of alder on the opposite side of the plot. Rows planted with alder were numbers 1, 2, 3, 4, 6, 7, 8, 10, 11, 13, 18, and 22.

The soil was a silt loam of the Padus series overlying sand and gravel at depths of 30 to 60 cm. The site was plowed to a depth of 16 cm, disked, and harrowed prior to planting. Soil samples were taken at 4-cm depth intervals to 16 cm in the plow layer of this soil and analyzed for total Kjeldahl nitrogen. Weeds were controlled with a combination of mechanical and hand cultivation and directed herbicide spray.

An irrigation gradient was superimposed on the plot at an angle of 90 degrees to the alder/poplar gradient. Analyses showed little evidence of interaction between irrigation and the species or clonal mixtures.

Tree heights were measured at the end of each growing season for 3 years. Diameters (15 cm above the first year's terminal bud scar) were measured at the end of the second growing season only. The relation of Populus height growth to the presence of Alnus was analyzed by regression. The dependent variable was the mean tree height in each Populus row. The independent variables were distance from a given Populus row to the nearest Alnus row and the percent of Alnus within various distances of the Populus row. Because of the planting design used, the percent of Alnus varied with distance from the Populus row. Consequently, distances of 2.4, 4.9, and 6.1 m either side of the Populus rows were selected to determine the "percentage of Alnus" that related best to Populus growth.

The roots of three alder trees in the Alnus/Populus mixed planting were excavated during their second growing season. A piece of root with attached nodules was removed from each tree and immediately assayed for nitrogenase activity. For the assay, root incubation techniques described in Dawson and Gordon (1979) and a portable gas chromatograph for the acetylene reduction assay (Mallard and others 1977) were used. The assay was performed to confirm N_2-fixation by Alnus nodules in the field plots of the study.

The plantation was coppiced after the third growing season and aboveground tissue was removed from the site. Soil samples were taken in spring following the fourth growing season. Three interior Alnus trees in each of rows 7, 11 and 15 were randomly selected as foci for soil sampling. Row 7 had Alnus rows on either side, row 11 had a row of Populus on one side and a row of Alnus on the other, while row 15 had rows of Populus on either side. Soil samples were taken with a soil probe adjacent to an alder stem and at 15, 30, 45, and 60 cm distances at a randomly selected azimuth for each distance from a stem. The probe samples were taken to a depth of 16 cm and divided into 4-cm depth increments. Soil samples were oven dried at 70°C and sieved through a 2-mm mesh screen prior to soil nitrogen determination using a micro-Kjeldahl procedure. An ANOVA was performed using a nested design to determine the variation in soil nitrogen concentration around Alnus stems associated with composition of adjacent rows of trees, depth of soil sample, and distance of sample from alder stem. Nitrogen concentrations from the same distance from stems within sample rows were compared with soil nitrogen concentrations from corresponding depths prior to tree planting using a t-test.

RESULTS

Height of Populus increased with increased Alnus in the mixture and with proximity to the nearest Alnus row. The maximum Populus height occurred in the area of the plot with the highest proportion of Alnus. This Populus row (row 9) was bounded on either side by Alnus, which constituted 66 percent of the mixture for a 4.8-m-wide strip. Average height of 3-year-old Populus in row 9 was 4.9 m (21 percent higher than the Populus in rows 25 and 26). Another single Populus row (row 5) had an anomalous low height. Consequently, this low value was discarded from Populus growth analyses. Alnus height growth was considerably slower, averaging only 55 percent of the average of all Populus at the end of 3 years (2.5 vs. 4.5 m).

Coefficients for regressions show that in a 3-year-old plantation, Populus height increases with increasing Alnus in the mixture and decreases with distance the Populus is from the Alnus. Both independent variables were significantly related to Populus height growth ($P = 0.05$).

Other regressions were run to test for possible bias from the Populus clonal mixture and for possible plot border effects. Although there was no noticeable height growth difference between the two Populus clones at the end of the second year, there was a significant height difference between them at the end of the third year. Also, the two clones were not randomly distributed over the plot but tended to be segregated by rows. Consequently, the mean row tree height was adjusted by an amount that depended on the relative proportion of the two clones in the row and the ratio of the average height of each clone. However, analysis using unadjusted data still resulted in R^2 values of 0.85 to 0.88, and deletion of all Populus rows containing some of both clones (rows 9, 21, 23, 25 and 26) resulted in R^2 values of 0.92 and 0.98. Therefore, it seems that although the mixture of two Populus clones complicated the analysis somewhat, it did not change the interpretation of the results. In all cases the two independent variables, distance and percent Alnus, were significant regardless of the order in which they were entered into the equation, and the model had a consistently good fit as evidenced by the high R^2.

It is apparent that Populus height growth decreases sharply near the plot border. To test whether plot border effects were unduly influencing the model, regressions were run using adjusted clonal height data and deleting the three border rows (rows 24, 25, and 26). The effect on the model of deleting the three border rows was minor; R^2 values still ranged from 0.83 to 0.92.

Since diameter growth of the two Populus clones was markedly different throughout the study, diameter was not used as a variable to test treatment response. However, since both diameter and height of Populus were related similarly to Alnus, it follows that proximity to Alnus increases Populus biomass as well as height growth.

The three samples of root nodules assayed were capable of reducing acetylene to ethylene, indicating nitrogenase activity and, thus, N_2-fixing capability of the planted A. glutinosa.

Soil nitrogen concentration in the top 16 cm of soil at this study site prior to planting was uniform with no significant differences among depths and little variation among samples from the same depth. Soil nitrogen concentrations of the plow layer before planting were 966 mg/kg dry weight in the top 4 cm of soil, 986 at the 4-8 cm depth, 962 at the 8-12 cm depth, and 888 at the 12-16 cm depth.

Analysis of variance revealed highly significant differences in total soil nitrogen concentration after 3 years around Alnus stems ($\alpha = 0.0009$) and these differences were associated with composition of rows adjacent to alder. Levels of total nitrogen concentration were highest where the Alnus was bracketed by Populus, and showed a 13 percent increase in soil-nitrogen concentration over levels measured prior to planting. Soil nitrogen concentration was only 1 percent higher than initial levels where alder had an adjacent row of poplar and an adjacent row of alder. Soil nitrogen concentration was lowest, with a significant net nitrogen loss of 10 percent where alder was associated with rows of alder on either side.

Soil nitrogen concentration around alder stems also varied significantly by depth ($\alpha = 0.0001$). Nitrogen concentration was highest in the top 4 cm of soil. Significant losses in soil nitrogen from the continuous Alnus strip were greatest at depths from 4-12 cm.

The distance from the alder stem at which soil samples were taken was not associated with significant change in soil nitrogen

concentration. There was no significant interaction between composition of adjacent rows and distance from alder stem.

DISCUSSION

A contiguous plot of pure Populus (same two clones as in the mixed plot) was fertilized annually with a gradient of NH_4NO_3. It was therefore possible to compare height growth response in fertilized Populus with that in an Alnus/Populus mixture. Since the plot treated with commercial fertilizer was planted earlier (August 1976 compared with May 1977 for the Alnus/Populus mixture), the tree heights of the mixed plot were adjusted upward by assuming that the untreated control portions of each plot (rows 24-26, which had no fertilizer or contained no Alnus) would have otherwise had equal height growth. This assumption resulted in increasing the tree heights of the mixed plot by 0.2 m. At the end of 3 years, maximum Populus height from commercial fertilizer was 5.25 m, compared with about 5.10 m for the adjusted heights from the mixed plot. Thus, the height difference between the two treatments was 0.15 m or 3 percent greater in the commercial fertilizer plot. If the difference in planting date were ignored, the height growth difference at 3 years would be 0.35 m or 7 percent.

Although more Alnus was better from the standpoint of Populus growth, Alnus growth lagged considerably behind that of the Populus. Similar results with European black alder and hybrid poplar have been reported by Wittwer and Immel (1977) and for red alder and black cottonwood by Harrington and others (1979). It was evident in this study that single rows of Alnus would soon be completely shaded by the Populus and perhaps eventually eliminated from the mix. It appears that Alnus may have difficulty surviving when mixed with Populus except perhaps for shorter rotations such as the 2-year coppice tested by DeBell and Radwan (1979) or on sites relatively favorable to Alnus (Harrington and others 1979). One strategy might be to interplant Alnus with the realization that it may be suppressed and eliminated from the plantation before harvest. There is also the possibility that Alnus growth can be substantially improved by selection and breeding. A series of sequential selections of Alnus glutinosa grown from seed in a greenhouse study resulted in the identification of fast-growing Alnus clones that performed as well as a fast-growing Populus clone in a controlled environment optimized for hybrid Populus (Bajuk and others 1978).

Alnus in this study was effective in symbiotically fixing N_2 as demonstrated by acetylene reduction ability and the zones of soil N accretion around some individual Alnus stems.

One apparently anomalous finding was that a row of poplar with many rows of nitrogen-fixing alder on either side did not grow as rapidly as Populus intermixed with Alnus. This led us to investigate the effects of hybrid poplar on the accretion of nitrogen in soil around alder stems. Since alder height growth at the end of three years in this plantation averaged 45 percent less than poplar height growth, and since relative growth rates remained constant after coppicing, the alder was shaded by the poplar at least during the 3 years prior to the time of our soil sampling. Some alder mortality was occurring in the fifth year of growth in single and double rows of alder. This shading may have resulted in tissue death and decay with release of N into soil. Similarly, input of nitrogen from tissue killed by poplar allelochemicals is possible. Younger and Kapustka (1982) note an allelochemic effect of Populus tremuloides Michx. on nitrogen fixation by Alnus rugosa (Du Roi) Spreng. in northern Wisconsin, and work in progress at the Forestry Department of Laval University in Quebec City indicates that phenolic acids present in leaf or bud leachates and extracts of Populus balsamifera L. are inhibitory for the juvenile development of Alnus crispa var. mollis Fern. (Thibault, personal communication). The competitive factors of shading and possible allelopathy due to poplar in our plantation study cannot be excluded as causes for early nitrogen accretion in soil around alder grown in close proximity to hybrid poplar. Leaf, twig, nodule, and fine-root tissue sloughed from plants would occur in highest quantities near the soil surface, perhaps explaining the significant differences in soil nitrogen concentration associated with depth of soil sample.

Hansen and Dawson (1982) found that localized regions of soil nitrogen accretion occurred within 15 cm of stems and in the top 4 cm of soil in a 2-year-old, 1 x 1-m plantation of A. glutinosa. This pure alder plantation consisted of clones that suffered severe frost damage. However, soil sampled away from this localized zone showed a net decrease in total soil nitrogen concentration. This localized pattern of soil nitrogen accretion conformed to the zone of maximum root activity in the 2-year-old plantation. Alder roots and soil nitrogen accretion are more extensive in the upper soil stratum of the

4-year-old plantations in this study, consistent with the differing results. Recent measurements in a 3-year-old A. glutinosa plantation growing vigorously in a well-drained terrace site in southern Illinois revealed no net increase in soil nitrogen concentration (Dawson, unpublished). Gadgil (1971) subjected nitrogen-fixing lupine plants to shading and defoliation stress in greenhouse experiments. The results suggested that damage to lupine plants could increase nitrogen availability to Pinus radiata seedlings planted in the same substrate. These observations lend support to the suggestion that early soil nitrogen accretion around nitrogen-fixing A. glutinosa may be related to plant stress.

Nitrogen losses from soil around alder planted in contiguous rows may be due to the retention of symbiotically fixed nitrogen by alder in growing tissue together with a net uptake of combined nitrogen from soil by alder. When soil is plowed, oxygen diffusion into soil is facilitated, thereby increasing the potential for nitrification by soil bacteria. Nitrate resulting from this aerobic process is readily leached out of surficial soil. Where this loss is not balanced by nitrogen inputs, such as those from nitrogen-rich alder litter and sloughed root tissue, net losses are easily possible. Bollen and Lu (1968) found high nitrification rates in red alder stands. Increased nitrification could have resulted in both increased leaching loss and increased uptake of nitrate with increased percentages of alder in our mixed planting. The effects of coppicing and irrigation in this study on alder root dynamics and nitrogen transformations in soil are not known. Further study will be required to explain fully the differences in soil nitrogen that we found.

We conclude that the configuration of mixed alder/poplar plantations is important if an early increase in potential nitrogen fertility of soil is expected. We also suggest that stress may precipitate early input of nitrogen into soil around nitrogen-fixing trees. Thus early nitrogen input may be inconsistent with greater longterm inputs of nitrogen where nitrogen-fixing nurse trees are completely inhibited or eliminated in young mixed plantations.

LITERATURE CITED

Bajuk, L. A., J. C. Gordon, and L. C. Promnitz. 1978. Greenhouse evaluation of the growth potential of Alnus glutinosa clones. Iowa State J. Res. 52:341-349.

Bollen, W. B., and K. C. Lu. 1968. Nitrogen transformations in soils beneath red alder and conifers. In: Biology of alder. p. 141-148. USDA Forest Service, Pac. NW For. Range Exp. Sta., Portland, Oregon.

Dale, M. E. 1963. Interplant alder to increase growth in strip-mine plantations. USDA Forest Serv. Res. Note CS-14, 4 p.

Dawson, J. O., and J. C. Gordon. 1979. Nitrogen fixation in relation to photosynthesis in Alnus glutinosa. Bot. Gaz. 140:S70-S75.

Dawson, J. O., P. J. Dzialowy, G. Z. Gertner, and E. A. Hansen. 1983. Changes in soil nitrogen concentration around Alnus glutinosa in a mixed short-rotation plantation with hybrid Populus. Can. J. For. Res. (In press).

DeBell, D. S. 1975. Short rotation culture of hardwoods in the Pacific Northwest. Iowa State J. Res. 49:345-352.

DeBell, D. S., and M. A. Radwan. 1979. Growth and nitrogen relations of coppiced black cottonwood and red alder in pure and mixed plantations. Bot. Gaz. 140:S97-S101.

Finn, R. F. 1953. Foliar nitrogen and growth in certain mixed and pure forest plantings. J. For. 51:31-33.

Gadgil, R. L. 1971. The nutritional role of Lupinus in coastal sand dune forestry. II. The potential influence of damaged lupin plants on nitrogen uptake by Pinus radiata. Plant and Soil 34:575-593.

Gordon, J. C., and J. O. Dawson. 1979. Potential uses of nitrogen-fixing trees and shrubs in commercial forestry. Bot. Gaz. 140:S88-S90.

Hansen, E. A., and J. B. Baker. 1979. Biomass and nutrient removal in short rotation intensive culture plantations. In: Proc. Symposium on the impact of intensive harvesting on forest nutrient cycling. p. 130-151. State Univ. of New York, Syracuse, NY.

Hansen, E. A., and J. O. Dawson. 1982. Effect of Alnus glutinosa on hybrid Populus height growth in a short-rotation intensively cultured plantation. Forest Sci. 28:49-59.

Harrington, C. A., D. S. DeBell, and R. F. Strand, 1979. An experiment in biomass production: results from three consecutive harvests of cottonwood and alder. In Proc. of Solar 79 Northwest, p. 363-366. Seattle WA.

Mallard, T. M., C. S. Mallard, H. S. Holfeld, and T. A. LaRue. 1977. Portable gas chromatograph for the acetylene reduction assay for nitrogenase. Anal. Chem.:1275-1277

McIntyre, A. C., and C. D. Jeffries. 1932. The effect of black locust on soil nitrogen and growth of catalpa. J. For. 30:22-28.

Miller, R. E., and M. D. Murray. 1978. The effect of red alder on growth of Douglas-fir. In Utilization and management of alder (D. G. Briggs, D. S. DeBell, and W. A. Atkinson, compilers), p. 283-306. USDA Forest Serv. Gen. Tech. Rep. PNW-70.

Plass, W. T. 1977. Growth and survival of hardwoods and pine interplanted with European alder. USDA Forest Serv. Res. Pap. NE-376. 10 p.

Red'ko, G. I. 1958. Influence of the black alder (Alnus glutinosa Gaertn.) on the productivity of the Canadian poplar (Populus canadensis Mich.) TT 66-61093. 4 p. US Dep. Comm. Clearinghouse for Fed. Sci. Tech. Inf. Springfield, VA.

Tarrant, R. F. 1961. Stand development and soil fertility in a Douglas-fir-red alder plantation. Forest Sci. 7:238-246.

Tarrant, R. F., and J. M. Trappe. 1971. The role of Alnus in improving the forest environment. Plant Soil, Special Vol.:335-348.

Van Der Meiden, H. A. 1961. De els in populierenbeplantingen. (Alder in mixture with poplar.) Nederlands bosbouw tiddschrift 33:168-171.

Wittwer, R. F., and M. J. Immel. 1977. A comparison of five tree species for intensive fiber production. For. Ecol. and Manage. 1:249-254.

Younger, P. D., and L. A. Kapustka. 1982. Acetylene reduction (N_2 fixation) by Alnus rugosa (DuRoi) Springel and allelochemic effects of Populus tremuloides (Michx.) in the northern hardwood forest. Amer. J. Bot. (in press).

Zavitkovski, J., E. A. Hansen, and H. A. McNeel. 1979. Nitrogen-fixing species in short rotation systems for fiber and energy production. In Symbiotic nitrogen fixation in the management of temperate forests (J. C. Gordon, C. T. Wheeler, and D. A. Perry, eds.), p. 388-402. For. Res. Lab., Oregon State Univ., Corvallis.

DEVELOPING ALNUS FOR USE IN INTENSIVE CULTURE[1]

Richard B. Hall, Gregory A. Miller, Terry L. Robison
and Oghenekome U. Onokpise[2]

Abstract.--Provenance tests and one clonal test have been analyzed to provide guidelines for the continuing efforts on the genetic improvement of Alnus. Observations also are made on the need for experiments with other silvicultural alternatives that might be applied to the intensive culture of alders.

Introduction

Alnus was among the first genera to be recognized as having the potential for intensive culture (Dickman 1975). This promise was based both on growth and yield properties and the ability of alders to symbiotically fix nitrogen. In the Pacific Northwest, Alnus rubra has proved to be a leading candidate for intensive culture, both in pure stands and in mixture with Populus trichocarpa (DeBell and Radwan 1979; Harrington et al. 1979). In the eastern United States the value of Alnus for intensive culture is less certain at this time. No yield data on large, pure alder plantings have been developed. The nitrogen-fixing ability of Alnus in mixture with Populus has been established, but the lack of height growth compatability (Hansen and Dawson 1982) and potential allelopathic relationships (Dawson et al. 1983) in such mixtures have called this approach into question. Mixtures with other species have shown some promise (Plass 1977; Wittwer and Immel 1977) but have not been evaluated in much detail.

One major limitation in evaluating the contribution that Alnus can make to intensive culture in the north central United States has been the lack of identified selections, preferably clones, that could be relied on to perform well. There are no tree-form alders native to the eastern United States, so interest has centered on exotics; Alnus glutinosa in particular (Hall and Maynard 1979). Genetic evaluation of Alnus glutinosa in this country began with Funk's (1973, 1979) test of 15 provenances on strip mine spoils in Ohio. In 1976, we began collecting additional Alnus seed sources. In 1979, we established new test plantations to augment Funk's study, both in terms of the range of germplasm evaluated and the types of U.S. sites considered (Robison et al. 1978). This paper will review the results from the first four growing seasons of those tests and from some related studies to provide an assessment of the potential of Alnus for intensive culture and to recommend the continuing steps needed to develop the best genetic material for this use. Information on general approaches to the genetic improvement of Alnus also has been given in two previous papers by our group (Hall and Maynard 1979; Robison and Hall 1981).

Materials and Methods

Most of the data reported in this paper were collected as part of our annual fall measurements in two provenance plantings, one located on the U.S. Forest Service's Harshaw Farm in northern Wisconsin, the other on Iowa State University's Rhodes Farm in central Iowa. The detailed descriptions of these planting sites, establishment procedures, and the experimental design of the plantations has been reported elsewhere (Maynard and Hall 1980). In addition to the A. glutinosa provenances that were the main focus of these tests, the plantation at Harshaw included several other alder species planted in the border rows. This included one Italian and one Belgian seed orchard collection of A. cordata, one Czechoslavakian and one Netherlands provenance of A. incana, one Idaho source of A. rubra, and one hybrid progeny of A. incana X A. glutinosa produced in Finland. At the beginning

[1]Journal Paper No. J-10993 of the Iowa Agriculture and Home Economics Experiment Station, Ames, Iowa. The work was supported by Station Project 2210 (NC-99 Regional Tree Improvement) and Cooperative Aid Agreement 13-721 with the U.S. Forest Service Intensive Fiber Yield Project.

[2]Authors are Professor and three Research Assistants, respectively, in the Forestry Department, Iowa State University, Ames, Iowa 50011

of the second growing season at Harshaw, 82 A. incana plants from the Netherlands provenance were used to plant in gaps in the original plantation where tree mortality had occurred. Comparative data for Populus clones grown under similar field conditions at the Harshaw farm were supplied by Dr. E. A. Hansen of the U.S. Forest Service.

Each fall, the Rhodes plantation was evaluated for the production of flower buds. Based on the 1982 data, a comparison was made between flowering and nonflowering trees in those provenances in which several trees were flowering to detect any relationship of flowering to total tree height and to height growth during the 1982 season. The provenance test was analyzed as a split-plot design using the mean values for flowering and nonflowering trees on each plot.

To evaluate the performance of clonal selections, another test plantation was established at the Rhodes Farm in June 1981. Selections of good and poor phenotypes were made in older alder plantations in Ohio (Funk 1973, 1979) and Illinois (Phares et al. 1975). Six additional clones identified in a greenhouse growth experiment (Bajuk et al. 1978) were included, as was the clone of one exceptionally fast-starting border tree in the Rhodes provenance plantation. Rooted cuttings were produced from greenhouse stock plants (Hall and Maynard 1979) and were planted on a 1.5 m square spacing in a randomized complete block design with 10 trees per clone. In the fall of 1982, after two growing seasons, heights and diameters of the trees were measured, and the presence or absence of flowering was noted. Diameter measurements were taken near ground level at the point of minimum diameter between the lowest branch and the swelling of the root collar.

Age-age correlations were developed from two sets of data; the 4-year results of the Harshaw and Rhodes provenance tests and from stem-analysis data from 17-year-old trees harvested in Funk's (1973, 1979) Ohio provenance trial. The stem analysis was based on disks cut at 1.0 m intervals along the stem. A computer program was used to convert ring count and width measurements into estimated heights and volumes by years. Correlations were calculated based on individual tree values for both the provenance test data and the stem analysis data.

Genotype by environment (G x E) interactions were estimated by measuring a subset of 17 provenances growing at three locations: the Rhodes and Harshaw plantations and a plantation near the town of Humm Wye in southern Illinois. The Humm Wye planting was made in 1980 by the Forest Service on a level bottomland site with a spacing of 1.8 m by 3.0 m. There were eight trees per plot and four replications with the same 48 provenances included in the Iowa and Wisconsin tests. First-year measurements of survival and height growth at the Humm Wye planting were provided by Dr. Knud Clausen of the U.S. Forest Service. Height and diameter measurements at a height of 1.0 m were taken in July 1982 on all three plantations. A combined analysis of variance was computed for the three locations to estimate the statistical strength of the G x E interaction (Comstock and Moll 1963). Variance components also were estimated so the main effects of provenance and location and the G x E interaction could be expressed as a percentage of total phenotypic variation (Cockerham 1963).

The general linear model of the Statistical Analysis System (Helwig and Council 1979) was used in the computation of all provenance and clonal means, analyses of variance, and variance component estimates.

Results and Discussion

Table 1 summarizes the year by year height growth performance in the Iowa and Wisconsin plantations and shows a comparison with one of the better Populus clones grown at the same location in Wisconsin. As previously reported, the first-year survival in both plantings was 90 percent or better. At the end of four growing seasons, survival still was 83 percent at both locations. Because of the stump sprouting ability of Alnus few trees died completely even though many southern sources had suffered repeated winter dieback. In the 1980 establishment of the southern Illinois plantation, a summer drought period did cause up to 88 percent mortality of some of these same provenances. Southern provenances had the best first-year survival (up to 88 percent) under those stress conditions.

By selecting the best provenances it would seem that first year height growths of 0.5 to 0.8 m could be achieved. However, herbaceous competition seems to thrive around the base of young alders, and the tendency of alders to produce many low branches in their first year makes chemical control of these weeds difficult. Therefore, alternative methods of producing alder planting stock should be sought that will give better first-year growth potential to keep pace with associated trees such as Populus hybrids and ahead of the weed competition. This study utilized 3- to 4-month-old containerized planting stock (Maynard and Hall 1980). One promising alternative that should be considered is 2-0 nursery stock.

After establishment, the best alder provenances were capable of making about 1 m of additional height growth each year at Harshaw. This growth rate places the alder progressively further behind the height growth of the better Populus clones. In Iowa, the annual height growth varied widely, depending on weather conditions. In 1980 and 1981, which were drier years, the best provenances were not capable of growing more than 0.75 m in height. But in 1982, a year with abundant moisture, all trees averaged 1.5 m of height growth, and the best trees grew 2 m. This indicates that height growth of A. glutinosa will fluctuate widely, depending on moisture status in a given year. Presumably, growth on sites of different water-holding capacity

Table 1. Overview of growth by year and location. Populus data are for plots on the same farm, but for the years 1980, 1978, 1979, and 1980, respectively.

--------Rhodes, Iowa--------				--------Harshaw, Wisconsin--------			
		Average Growth (cm)			Average Growth (cm)		
Year	Conditions	All Trees	Best Prov.	Conditions	All Trees	Best Prov.	Populus Clone 5262
1979	Established in late May	63	84	Established in mid June	33	48	97
1980	Canker disease problems	48	70	"Normal"	74	101	105
1981	Dry spring and summer	38	75	"Normal"	69	110	157
1982	"Harsh" Winter Abundant summer moisture	153	199	Late frost followed by canker problems	40	94	231

would be similarly affected. Another factor that may have contributed to the 1982 burst of growth at the Rhodes plantation was the crown closure, and subsequent elimination of understory competition, that occurred in the plots with larger trees.

Table 2 lists the 4-year height growth and rankings by height growth of the individual provenances at the Iowa and Wisconsin test sites. At this stage (age) of development, the best provenances for use in Iowa come from scattered areas, primarily in central Europe: central and southern Germany, Hungary, Ireland, the Netherlands, and Denmark. The last two provenances may represent secondary sources that originally were introduced from other areas of Europe. Superior performance at the Wisconsin site was restricted to a more geographically confined set of provenances from northern and eastern Europe: Poland and the Baltic States. These results are consistent with those of Funk (1979) in his earlier provenance test, but they have the value of extending our knowledge of the variation patterns and identifying sources of superior germplasm outside the geographic region sampled by Funk. Patterns of climatic suitability have been evident from the beginning of the second growing season (Maynard and Hall 1980). Some additional winter damage has occurred in southern provenances since that report; e.g., provenance 962 from northern Italy has been surpassed in the Iowa plantation by more hardy provenances because of low-level damage it has suffered in the last 2 years. Because such marginally adapted provenances still should have considerable value in an interprovenance breeding program, preparing for the next cycle of selection by identifying useful provenances at the end of 2 years probably is warranted.

In addition to the overall growth patterns, some other potentially useful traits have been noted in these studies. The provenances from the southeastern portion of the A. glutinosa range (800 numbers) produce much larger leaves and the best annual growth rates. Mediterranean provenances (numbered in the 900's) tend to produce a fine, upright branch structure. If these traits could be combined with the coldhardiness of the more northern provenances by breeding, it could lead to substantial improvements for total growth, form, and type of biomass produced. Another important trait is likely to be resistance to the Phomopsis-like canker that has been observed in these tests and by other researchers (Oak and Dorset 1981). On the basis of observations to date, it is not certain that any provenance is totally immune to the disease, but all provenances do produce individuals that have some resistance and/or ability to recover. Outbreaks of the canker have followed periods of heat, drought, or frost stress in the plantations, and genetic variability in canker resistance might trace back to a genotype's response to those stresses.

To expand our knowledge of G x E interactions the height and diameter rankings of 17 provenances were analyzed across a north/south transect represented by the northern Wisconsin, central Iowa, and southern Illinois plantations. The results are given in Table 3. Provenance rankings for both height and diameter tend to follow the same pattern Northeastern provenances such as the Polish sources 561, 541, and 511 rank best in Wisconsin, but fall consistently in rank in the two more southern test sites. This change is even more striking for the Baltic and Scandinavian provenances (Table 2). Actual height growth is as good or better at the southern test sites, but other provenances benefit more from the longer growing seasons, milder winte etc., and surpass the northern sources in rank. F example, southern provenances such as the French 6 and Italian 962 improve their ranking considerably

Table 2. Average 4-year heights of Alnus glutinosa grown at two locations.

Provenance Number	Geographic Origin	Latitude (North)	Avg. Height in cm (Rank) Rhodes, IA	Harshaw, WI
118	Coote Hill, Ireland	54 5	374 (6)	252 (15)
127	Bandon, Ireland	51 46	310 (26)	225 (24)
131	Golspie, Scotland	58 15	233 (38)	202 (32)
151	Innerleithen, Scotland	55 38	324 (21)	205 (31)
172	Wrexham, N. Wales, U.K.	52 57	332 (18)	243 (18)
211	Oslo, Norway	59 40	213 (41)	218 (27)
213	Burgen, Norway	60 16	177 (42)	156 (37)
216	Steinkjer, Norway	64 12	121 (48)	147 (38)
221	Humieback, Denmark	56 0	411 (1)	241 (19)
222	Sakskobing, Denmark	54 45	292 (31)	218 (28)
261	Turku, Finland	60 25	146 (47)	164 (34)
281	Tartu, Estonia, USSR	58 10	318 (24)	270 (6)
291	Riga, Latvia, USSR	56 44	266 (34)	267 (7)
431	Uetze, W. Germany	52 25	376 (4)	245 (17)
451	Kinzig River, W. Germany	50 0	298 (30)	252 (14)
472	Offenburg, W. Germany	48 30	366 (9)	229 (23)
481	Ingolstadt, W. Germany	49 0	374 (7)	249 (16)
511	Naklo, Poland	53 8	368 (8)	273 (5)
541	Brzeziny, Poland	51 48	306 (27)	297 (3)
542	Bialowieza, Poland	52 30	299 (29)	289 (4)
561	Lezajsk, Poland	50 0	330 (19)	330 (1)
562	Bresesko, Poland	49 50	321 (22)	267 (8)
571	Kosteler, Czechoslavakia	50 1	352 (13)	300 (2)
582	Zvolen, Czechoslavakia	48 35	319 (23)	257 (12)
591	Gyor, Hungary	47 40	389 (3)	260 (11)
592	Kormend, Hungary	46 55	395 (2)	225 (25)
614	Scherpenzeel, Netherlands	52 50	375 (5)	234 (21)
633	Zurich, Switzerland	47 16	282 (33)	236 (20)
638	Lausanne, Switzerland	46 32	362 (11)	256 (13)
653	Nancy, France	48 48	332 (17)	213 (30)
682	St. Julien en Born, France	44 4	352 (14)	166 (33)
722	Novoselec, Yugoslavia	45 35	356 (12)	261 (10)
724	Durdevac, Yugoslavia	46 5	328 (20)	229 (22)
792	Sofia, Bulgaria	43 0	315 (25)	266 (9)
795	Klisura, Bulgaria	42 45	336 (15)	224 (26)
704	Kosti, Bulgaria	42 3	303 (28)	214 (29)
841	Sochii, USSR	43 36	250 (35)	106 (44)
843	Yalta, USSR	44 40	336 (16)	159 (36)
801	Hashtpar, Iran	37 30	170 (43)	73 (48)
803	Noor, Iran	36 35	157 (45)	96 (47)
911	Zamora, Spain	41 11	167 (44)	99 (45)
912	Pontevedra, Spain	41 52	154 (46)	99 (46)
962	Pordenone, Italy	46 2	364 (10)	161 (35)
973	Pinaura D. Lucca, Italy	43 49	226 (39)	146 (40)
975	Villa Basilica, Italy	43 48	285 (32)	146 (39)
981	Cosenza, Italy	39 10	219 (40)	109 (43)
985	Forli Del Sannio Is., Italy	41 39	249 (36)	130 (42)
901	Lamja, Greece	38 54	240 (37)	138 (41)

in comparing the northern to southern test sites. We have previously noted the wide differences in seasonal bud set behavior between northern and southern provenances (Maynard and Hall 1980). In a recent analysis of data on a subset of these same 48 provenances of A. glutinosa grown in Iowa, Wisconsin, Pennsylvania, and New Brunswick, similar north/south patterns were observed while east/west differences were not strong. For example, the correlation in first-year height growth for the trees grown in Iowa and Pennsylvania was 0.83 (DeWald 1982; DeWald et al. 1983). They also noted that southern provenances suffered less growth loss when grown on droughty mine spoil sites.

Table 4 gives an analysis of the strength of the genotype by environment interactions. For both height and diameter the interactions term is

Table 3. Provenance rankings within locations for height and diameter in July 1982. See Table 2 for meanings of provenance numbers.

	Height			Diameter		
Rank	Harshaw Wisconsin	Rhodes Iowa	Humm Wye Illinois	Harshaw Wisconsin	Rhodes Iowa	Humm Wye Illinois
1	561	592	962	561	592	962
2	541	614	592	541	614	722
3	511	591	481	591	481	481
4	722	481	722	511	591	592
5	591	962	614	722	722	451
6	481	511	682	724	962	682
7	451	722	511	633	511	511
8	633	561	451	481	795	795
9	614	795	724	592	724	714
10	724	682	795	451	561	633
11	131	724	591	795	682	591
12	222	451	561	614	541	614
13	592	222	633	222	222	561
14	795	541	975	131	451	222
15	682	633	541	962	131	131
16	962	975	222	682	633	541
17	975	131	131	975	975	975

Table 4. Combined analysis of variance to estimate the relative strength of provenance variation and genotype x environment interaction; based on 17 provenances measured at three locations in July 1982.

		Height		Diameter		
Source	df	MS	F	MS	F	Expected Mean Squares
Locations	2	28830		3.279		
Reps. (Loc.)	9	7002		0.915		
Provenances	16	11779	2.46*	1.443	2.37*	$\sigma_e^2 + 3.9\ \sigma_{P \times L}^2 + 11.7\ \sigma_P^2$
Provenances x Locations	32	4797	5.02**	0.608	3.13**	$\sigma_e^2 + 3.9\ \sigma_{P \times L}^2$
Error	144	955		0.194		σ_e^2

	Estimated Value for Variance Component			Percent of Total Phenotypic Variance	
	σ_e^2	$\sigma_{P \times L}^2$	σ_P^2	$\sigma_{P \times L}^2$	σ_P^2
Height	955	989	595	39.0%	23.4%
Diameter	0.194	0.109	0.072	29.1%	19.2%

Significance of the F test shown as * = significant at the 0.05 probablitiy level and ** = significant at the 0.01 level.

stronger than the provenance component. Therefore, we can conclude that the selection of Alnus in the north central United States, and probably its breeding as well, should be based on results at a number of geographically dispersed test sites. Recommendations for a specific area should be based on the most similar test site results and extrapolations from the other test sites. The three test sites discussed in this paper are separated by about 3.5 (Iowa/Wisconsin) and 4.5 (Iowa/Illinois) degrees of latitude. The east-west set of tests summarized by DeWald (1982; DeWald et al. 1983) cover an even greater span of mileage between test sites. This network probably is adequate for developing an overview of A. glutinosa performance in the region, but it is likely to miss some important variation related to local climates and, especially, sites.

To assess the progress in improving A. glutinosa for intensive culture, it is illustrative to return to a comparison with hybrid Populus clones. The mixed planting analyzed by Hansen and Dawson (1982) was grown at the Harshaw farm on a site very similar to the provenance test site. In the mixed planting, the average 3-year height of the alders was 2.5 m while the Populus hybrid clones averaged 4.9 m. In the provenance test, even the best provenances did not exceed an average height of 2.5 m at 3 years. However, as illustrated in figure 1, individual trees did exceed that height. The best 5 percent of the trees from the best provenances were more than 3.0 m tall. Hence, while the average performance of A. glutinosa provenances does not represent much hope for significant improvement, the range of individual tree variation should offer considerable raw material for a selection and breeding program. The Populus hybrids currently in use are the products of at least two stages of genetic improvement. Therefore, it is not surprising that one cycle of provenance selection in Alnus is insufficient to close the "improvement gap" between the two genera.

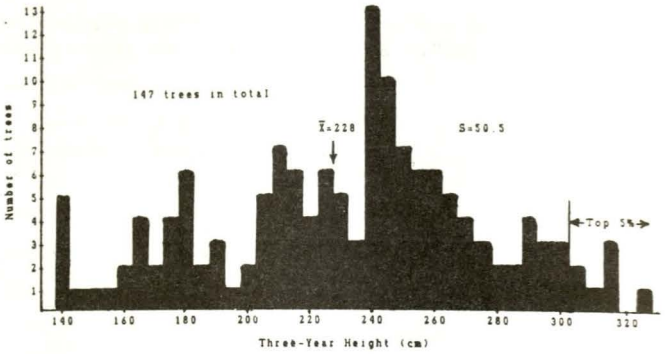


Figure 1. Frequency distribution of total 3-year heights for trees in the six best provenances grown at Harshaw, Wisconsin. Three trees that were less than 100 cm are not included on the graph.

Some data (Table 5) for other alder species are available from the unreplicated plantings of border and mortality replacement trees at the Harshaw site. Both the A. cordata and A. rubra plantings had poor growth and survival because of a lack of winter-hardiness. It is doubtful that sufficient hardiness can be found in these species to make them directly useful in the north central United States. Tests in more southern locations should be attempted. On the basis of the two provenances of A. incana that were studied, this species does show considerable promise and should receive more attention. The best trees in the Netherlands provenance were 0.5 m taller at three years than any of the A. glutinosa trees. A. accuminata from South America and several Asiatic Alnus species also may have value for use in the north central region (Hall and Maynard 1979), but no field tests have been conducted.

Just as hybrids have formed the basis of tree improvement in Populus, they may hold out the best

Table 5. Three year performance of other Alnus species at the Harshaw, Wisconsin, provenance test site.

Species	Number Planted	Number Surviving	Height (cm) Range	Height (cm) $\bar{X}$	Height (cm) S
A. cordata	40	3	16 - 57	31	-
A. incana					
Czech.	9	6	70 - 250	135	64
Neth.	82	58	35 - 380	211	84
A. incana x A. glutinosa (Finland)	19	7	27 - 157	92	53
A. rubra (Idaho)	11	0	-	-	-

hope for substantial improvements in Alnus (Hall and Maynard 1979). The relatively poor performance (Table 5) of the one hybrid tested probably is more reflective of the extreme northern origin of the parents than of the general value of the A. incana x A. glutinosa cross. Hybridization work should proceed with parents that have been selected for our latitudes and climates. Intraspecies crosses involving selected trees from diverse geographic origins may also allow for the combining of desirable traits and give rise to heterotic growth. Such systems are yielding very successful results in the Populus breeding programs in Europe.

One other feature of Populus tree improvement that has yet to be applied in large scale to Alnus is the cloning of selected genotypes. Alnus clones can be established from greenwood cuttings (Hall and Maynard 1979) or from tissue culture (Garton et al. 1981), but neither approach is efficient enough for large-scale use at this time. As noted in the last column of Table 6, no clone gave 100 percent survival of the 10 plants per clone set out in the experiment. Average survival was only 56 percent. This contrasts to the much better survival of seedlings that was discussed earlier, and it probably is related to the difficulty in getting a well-established root system on the cuttings before they are field-planted. In addition, rooting difficulties could be expected to contribute to the variation observed within and between clones. In general, the trees with better survival also ranked highest in growth characteristics (Table 6).

Table 6 also provides some insight into the potential for phenotypic selection and selection at young ages in Alnus. Most of the trees selected for superior growth in the older Illinois and Ohio plantations gave rise to clones that ranked above average in growth after 2 years. The trend was more consistent for diameter than for height. The six clones that were selected under greenhouse conditions (Bajuk et al. 1978; Gordon and Wheeler 1978) have performed relatively well the first 2 years in the field. It will be important to

Table 6. Results of 2-year clonal study at Rhodes, Iowa. Clones are arranged in rank order by decreasing stem diameter.

------Clone------		Field	Diameter	----Height----		Number of Trees
Number	Source[1/]	Rating[2/]	(mm)	(cm)	(Rank)	Flowering/Surviving
42	IL	+	46.4	150.7	7	0/9
37	IL	+	36.7	179.5	1	0/6
14	OH	+	33.8	173.0	2	0/8
1-26	Ba		33.7	155.4	6	0/7
21	OH	-	33.4	159.8	4	0/5
1-23	Ba		31.8	145.0	10	0/8
40	IL	-	31.1	160.7	3	0/7
2-50	Ba		30.4	138.5	12	0/4
15	OH	+	26.1	113.4	20	0/8
41	IL	+	25.1	135.4	14	0/8
44	IL	+	24.8	156.5	5	0/2
33	IL	+	23.9	144.9	11	0/7
34	IL	-	23.2	134.0	15	4/7
3-21	Ea		23.0	148.5	8	0/2
32	OH	-	22.6	123.3	18	0/6
39	IL	-	22.2	135.8	13	4/8
5-50	Ba		21.8	131.0	16	0/1
30	OH	+	20.9	94.0	25	0/5
46	Rh		20.8	146.1	9	3/7
3-13	Ea		20.3	129.3	17	0/6
45	IL	-	19.4	120.6	19	3/5
19	OH	-	18.6	108.8	21	0/5
17	OH	-	17.7	84.5	27	0/4
25	OH	-	17.6	106.8	22	0/5
43	IL	-	16.8	90.4	26	0/5
20	OH	+	15.4	99.5	23	0/2
16	OH	-	14.9	97.3	24	0/4

1/ Location of ortet from which the clone was derived: IL = Illinois plantation; OH = Ohio provenance test; Ba = Bajuk greenhouse experiment; Rh = Rhodes, Iowa, provenance test.

2/ For field ratings a "+" indicates the ortet was one of the largest trees in the planting and a "-" indicates the ortet was one of the smallest trees in the planting.

continue monitoring field performance as a guide to the value of selection based on short-term physiological tests and controlled-environment growth.

The selection that was made from an exceptionally fast-starting border tree in the original Rhodes provenance trial was particularly interesting. Two-year height growth was quite good in the ramets just as it was in the ortet. After the selection was made, however, the ortet began flowering heavily, suffered from the Phomopsis-like canker, and lost its growth superiority. The ramets of this selection are now following a similar pattern (Table 6).

Overall clonal repeatability (broad sense heritability) at 2 years was 0.32 for height and 0.59 for diameter. Assuming there is sufficient similarity between this study and the way a mass selection/clonal propagation program based on the provenance tests would operate, an estimate of potential genetic gain in height can be calculated. The population values are taken from figure 1. If the best 5 percent of the phenotypes were taken this would represent a selection intensity (i) of 1.4. The standard deviation of the population at 3-years-of-age is 50.5 cm. Applying the estimate of 0.32 for clonal heritability, the potential genetic gain (ΔG) is:

$$\Delta G = ish^2_{BS} = (1.4)\ (50.5\ cm)\ (0.32) = 22.6\ cm$$

Based on the overall population mean of 228 cm (figure 1), this would represent a 10 percent gain. To achieve greater genetic gain, it will be necessary to work with larger populations (so stronger selection intensities can be used), develop selection methods that are better than mass selection, and/or improve on cloning techniques so that nongenetic variation such as variable rooting does not lower the heritability of the desired traits. It does seem from this study that juvenile diameter growth is more strongly inherited and bears a better relationship with ortet performance than does juvenile height growth. In as much as each provenance is represented by a maximum of 32 trees at each test site (Maynard and Hall 1980), there is a need to establish much larger populations of the most promising provenances to support future selection and breeding efforts.

The age at which selections can first be made reliably is an important consideration for tree improvement. To study this question in A. glutinosa we have analyzed two sets of available data: the annual measurements of individual tree heights in the current provenance tests and stem analysis measurements from trees in the earlier provenance test planted by Funk (1973) in Ohio. Table 7 gives the correlation matrix for age-to-age correlations in the 4-year-old provenance tests. As expected, first-year performance was not highly correlated with later performance, especially in the Wisconsin planting where southern provenances did grow well until after the first winter. The trend of improving correlations shown in the first 4 years (Table 7) does

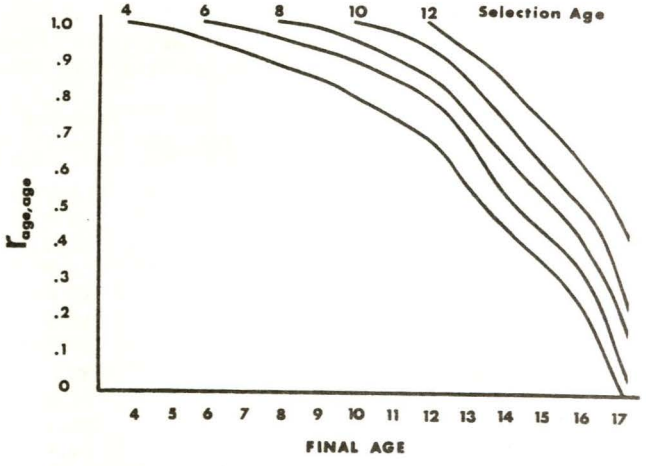


Figure 2. Correlations in total height between potential selection ages and harvest ages based on a 17-year-old provenance study in Ohio.

Table 7. Age-age correlations in total height of individual trees in the provenance tests. All correlations are based on over 1100 data points and are significant at the 0.0001 probability level.

	---------Rhodes, Iowa--------- Correlated with Height at:				--------Harshaw, Wisconsin---- Correlated with Height at:			
Height at	Age 1	Age 2	Age 3	Age 4	Age 1	Age 2	Age 3	Age 4
Age 1	1.00	0.79	0.71	0.61	1.00	0.60	0.28	0.14
Age 2		1.00	0.81	0.74		1.00	0.73	0.52
Age 3			1.00	0.86			1.00	0.85
Age 4				1.00				1.00

carry on in older trees as demonstrated in figure 2. However, beyond age 12, the age-to-age correlations for total height begin to decrease once again. If we use an r=0.7 (r^2=0.50) as our guiding limit that we wish to stay above (Steinhoff 1974), then selections for short-rotation intensive culture of A. glutinosa should be made at about 1/2 to 2/3 of the planned rotation age.

However, height, per se, is not our primary objective. Instead, we usually are most concerned with volume as an improvement goal. At nearly all selection ages, diameter is at least as good as, if not 0.1 to 0.15 correlation units better than, height as a predictor of volume production at future

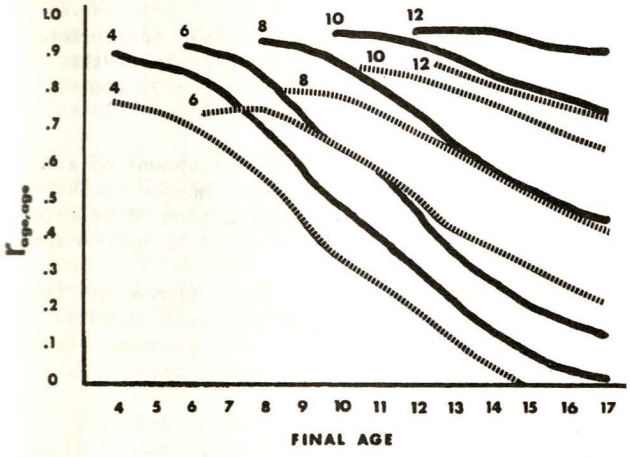


Figure 3. Correlations of height (IIIIIIIIIIII) and diameter (▬▬▬▬) with volume production for various selection and harvest ages. Based on a 17-year-old provenance study in Ohio. Selection ages are indicated at the left end of each curve.

ages (figure 3). This adds to our previous argument for placing greater emphasis on selection based on diameter growth in tree improvement for intensive culture (see earlier discussion in this paper and Hall 1982). What remains is to find an efficient way of screening diameter differences in large test populations. In breeding for intensive culture, we probably also need to look at correlations with coppice production (Hall 1982), but no such studies have been initiated.

The final point on which we have been able to collect information to date is the relationship between vegetative growth and flowering. Previous work in A. glutinosa has indicated that the sudden increase in flower production that some trees undergo is responsible for their poor vegetative performance (Münch 1936; Verweij 1977; Funk 1979). Early flowering (short generation time) is desired in tree breeding programs, but could reduce our progress in improving woody biomass production (Hall and Miller 1980). Therefore, we have been following this relationship closely in the Rhodes plantation. A few trees in the Hungarian provenances (591 and 592) formed flower buds at the end of their second growing season. These same trees flowered again more heavily in each of the next two growing seasons, and additional individuals in a number of other provenances began to flower. As can be seen in Table 1, provenances 591 and 592 continue to be among the tallest trees in the study despite their flowering precocity. When the flowering and growth data are analyzed across the 16 provenances that had several trees flowering at age 4 (Table 8), the flowering trees average almost 2/3 m taller. Flowering trees also had slightly higher average growth in the latest growing season, but this effect was not statistically significant at the 5 percent probability level. In their studies of A. glutinosa Verweij (1977) and Funk (1979) also have observed that some of the fastest-growing trees began flowering first. Between the ages of 6 and 10, many of the precocious trees in their tests began to fall behind in vegetative growth. We will contine to study the relationship in our plantation in an attempt to refine our knowledge of what is occurring at older stages. However, the fact that a positive relationship between flowering and vegetative growth exists through at least the first 4 years is encouraging for the prospects of breeding Alnus for short-rotation biomass production.

Table 8. Flowering in relationship to total height and growth of 16 provenances at Rhodes, Iowa--year 4.

	Number	Average in cm Total Height	1982 Growth
Flowering Trees	156	400	183
Non-Flowering Trees	310	334	174
Probability the means are same		0.0001	0.14

CONCLUSIONS

1. Cultural techniques for growing alders need attention while the genetic improvement effort continues. Planting stock alternatives, weed control during establishment, levels of acceptable stand competition, and coppicing techniques seem to be the most important voids in current understanding. An efficient method of cloning is needed so we can rapidly capitalize on superior individual selections.

2. Tremendous genetic diversity is present in the genus, but it needs much "repackaging" before we'll have exactly what we want.

   A. We will need to pay particular attention to stress tolerance and canker resistance.

B. Selection work will need to be done within each climatic zone, and probably by site class. For northern Wisconsin, emphasis should be placed on provenances from Poland and the Baltic States. For Iowa, and perhaps the central states in general, the emphasis should be on central European sources. For breeding work, selected parents from more northern and southern provenances should also be included in attempts to generate more optimal growing patterns over the season while retaining adequate winterhardiness. This also will help to maintain a broad genetic base in the breeding program.

C. Other speices of Alnus need to be evaluated. Alnus incana is likely to be of some use throughout the north central region. A. cordata may have value in central and southern states. A. accuminata from South America and several oriental species also deserve careful consideration. Inter- and intra-species breeding should proceed as rapidly as selected parents can be identified and flowering begins.

3. Although the present 4-year-old tests should not be used to project performance for more than an 8-year rotation, the data on climatic suitability should be reliable enough that we can begin to establish large populations of the most promising provenances. When these large populations reach the proper age, they can then be subjected to greater selection intensities to form the bases for long-range improvement efforts.

4. Diameter measurements need to receive greater emphasis in the selection of improved Alnus genotypes. Improvements in measurement techniques are needed before this will be practical for large scale programs.

Literature Cited

Bajuk, L. A., J. C. Gordon, and L. C. Promnitz. 1978. Greenhouse evaluation of the growth potential of Alnus glutinosa clones. Iowa State J. Res. 52:341-349.

Cockerham, C. C. 1963. Estimation of genetic variances. pp. 55-93. In: Hanson, W. D., and H. F. Robinson (eds). Statistical Genetics and Plant Breeding. Natl. Acad. Sci. - Natl. Res. Counc. Publ. 982.

Comstock, R. E., and R. H. Moll. 1963. Genotype-environment interactions. pp. 164-196. In: Hanson, W. D., and H. F. Robinson (eds.). Statistical Genetics and Plant Breeding. Natl. Acad. Sci. - Natl. Res. Counc. Publ. 982

Dawson, J. O., F. J. Dzialowy, G. Z. Gertner, and E. A. Hansen. 1983. Changes in soil nitrogen concentration around Alnus glutinosa in mixed, short rotation plantation with hybrid Populus. Can. J. For. Research. In press.

DeBell, D. S., and M. A. Radwan. 1979. Growth and nitrogen relations of coppiced black cottonwood and red alder in pure and mixed plantations. Bot. Gaz. 140:S97-S101.

DeWald, L. E. 1982. Juvenile performance in a range-wide provenance study of Alnus glutinosa (L.) Gaertn. M.S. Thesis. The Pennsylvania State Univ. 105p.

DeWald, L. E., K. C. Steiner, and K. K. Carter. 1983. Juvenile performance in three black alder plantations in the Northeast. Proc. 28th Northeastern Forest Tree Improvement Conf. In press.

Dickman, D. I. 1975. Plant materials appropriate for intensive culture of wood-fiber in the North Central Region. Iowa State J. Res. 49:281-286.

Funk, D. T. 1973. Growth and development of alder plantings on Ohio strip-mine banks. pp. 483-491. In: Ecology and Reclamation of Devastated Land. Vol 1. Gordon and Breach, New York.

Funk, D. T. 1979. Alnus glutinosa provenance trials on Ohio strip mines: Sixteen-year results. Proc. 1st North Central Tree Improvement Conf. Univ. Wisconsin, Madison, Wis. pp. 28-32.

Garton, S., M. A. Hosier, P. E. Read, and R. S. Farnham. 1981 In vitro propagation of Alnus glutinosa Gaertn. Hort. Science 16(6): 758-759.

Gordon, J. C., and C. T. Wheeler. 1978. Whole plant studies on photosynthesis and acetylene reduction in Alnus glutinosa. New Phytol. 80:179-186.

Hall, R. B., and C. A. Maynard. 1979. Considerations in the genetic improvement of alder. Proc. Workshop on Symbiotic Nitrogen Fixation in the Management of Temperate Forests. Oregon State Univ., Corvallis, Oregon. pp. 322-344.

Hall, R. B., and G. A. Miller. 1980. The role of physiology in tree improvement. Proc. 17th Canadian Tree Improvement Assoc. Meeting. Part 2:77-91.

Hall, R. B. 1982. Breeding trees for intensive culture. Proc. IUFRO Joint Meeting of Working Parties on Genetics About Breeding Strategies Including Multiclonal Varieties. Escherode, Federal Republic of Germany. pp. 182-193.

Hansen, E. A., and J. O. Dawson. 1982. Effect of Alnus glutinosa on hybrid Populus height growth in a short-rotation intensively cultured plantation. For. Sci. 28:49-59.

Harrington, C. A., D. S. DeBell, and R. F. Strand. 1979. An experiment in biomass production: Results from three consecutive harvests of cottonwood and alder. Proc. Solar 79 Northwest Symposium. Seattle, Wash. pp. 363-366.

Helwig, J. T., and K. A. Council (eds.). 1979. SAS User's Guide. 1979 Edition. SAS Institute Inc. Raleigh, N.C. 494p.

Maynard, C. A., and R. B. Hall. 1980. Early results of a range-wide provenance trial of Alnus glutinosa (L.) Gaertn. Proc. 27th Northeastern Forest Tree Improvement Conf. pp. 184-201.

Münch, E. 1936. Das Erlensterben. Forstwiss. Centralb. (Hamb.) 58:173-194.

Oak, S. W., and R. Dorset. 1981. Evaluation of mortality in a European black alder seed production area. Report #81-1-26, Forest Pest Management, U.S. For. Serv. State and Private, Ashville, N.C. Field Office.

Phares, R. E., R. C. Schlesinger, and G. A. Cooper. 1975. Growth, yield, and utilization of European black alder interplanted with black walnut. pp. 102-111. In: Impact of Inflation on the Management and Utilization of Hardwoods. Proc. 3rd Annu. Hardwood Symp. Hardwood Res. Counc. Statesville, N.C.

Plass, W. T. 1977. Growth and survival of hardwoods and pine interplanted with European alder. U.S. For. Serv. Res. Pap. NE-376. 10 p.

Robison, T. L., C. A. Maynard, J. Thomas, and R. B. Hall. 1978. A germplasm collection and evaluation program for Alnus glutinosa. Proc. 26th Northeastern Forest Tree Improvement Conf. pp. 73-85.

Robison, T. L., and R. B. Hall. 1981. Approaches to European alder improvement. Proc. 2nd North Central Tree Improvement Conf. pp. 65-77.

Steinhoff, R. J. 1974. Juvenile-mature correlations in ponderosa and western white pines. pp. 243-250. In: Proc. Joint IUFRO Mtg. S.02.04. 1-3, Stockholm, 1974, Session IV. Dept. Forest Genetics, The Royal College of Forestry, Stockholm, Sweden.

Verweij, J. A. 1977. [Research on provenances and progenies of alder (Alnus glutinosa, Alnus incana and Alnus cordata)] Rijksinstituut voor onderzoek in de bos-en landschapsbouw "De Dorschkamp," Wageningen, The Netherlands. Uitvoerig verslag. 15(1):1-23.

Wittwer, R. F., and M. J. Immel. 1977. A comparison of five tree species for intensive fiber production. For. Ecol. Manage. 1:249-254.

IRRIGATING FOREST PLANTATIONS

Edward A. Hansen[1]

Abstract.--Irrigating forest plantations cannot be justified economically on yield increases alone under present market conditions. Other factors such as bringing noncommercial land into high production, insuring a constant wood supply, or providing a means to dispose of wastewater can add to the value of increasing yields and may make irrigation feasible in certain situations.

A major reason for irrigating forests is to increase yields. However, yield increases alone do not offset the added costs of irrigation (Rose et. al. 1981). Other associated benefits of irrigation are the reduced costs for land, harvesting, transportation, and land taxes that result from growing more fiber on less acreage (Mace and Gregersen 1975). These benefits bring irrigation closer to a break-even point. Additional potential benefits of irrigation that have been identified are to provide a means to dispose of wastes, (Hansen et. al. 1980), insurance against drought (Rose and Kallstrom 1976), and a secure source of raw material to a mill that would be costly to shut down (Rose et. al. 1981). But these values are difficult to assess and have not been incorporated into economic analyses of forest irrigation.

Even though forest irrigation has been done experimentally for more than 50 years, I am aware of only one area with a large acreage of irrigated plantations--340,000 acres in West Pakistan (Sheikh 1974). Consequently, the forestry literature contains little discussion of irrigation strategy from a management or economic viewpoint. However, the agricultural literature contains much parallel information. This paper examines some of the reasons behind the decisions for irrigated farming and applies that reasoning to the irrigation of short rotation intensive culture (SRIC) plantations. Benefits and possible negative aspects of irrigation are discussed with illustrations from data collected in irrigated hybrid poplar plantations in northern Wisconsin.

[1]Research Forester, North Central Forest Experiment Station, Forestry Sciences Laboratory, Rhinelander, WI 54501

For purposes of illustrating benefits on yield, an idealized view of the relation of tree yield to soil moisture is shown in Figure 1. Although the shape of the yield function over the range of soil moisture is not known, we do know that for a particular species on a specific site no tree growth will occur both at some very dry condition, and at the other extreme of some very wet condition. Somewhere in between these two extremes of soil moisture, tree growth reaches a maximum, the exact optimum soil moisture level varying with tree species. The right hand portion of the function illustrates excessive soil moisture and represents the condition where drainage would increase tree growth. The left hand portion of the function illustrates soil moisture deficiency and represents the condition where irrigation would increase tree growth. It is this drier portion of the soil moisture range that is of interest in this discussion.

Why Irrigate

Tree growth within the humid temperate region varies widely over a range of soil moisture conditions. Under these climatic conditions, irrigating dry sites may possibly produce growth rates similar to those naturally occurring on the very best sites--other factors being the same. Irrigation may be thought of as merely a substitute for insufficient soil moisture storage capacity. Depending upon the existing soil moisture holding capacity, sites may range from being incapable of supporting tree growth without irrigation to showing no additional growth response to irrigation. The value of irrigation for different severities of soil moisture deficit on agricultural soils has been discussed by Greenshields (1955), Tharp and Crickman (1955), and Marr (1967). I have summarized these irrigation benefits

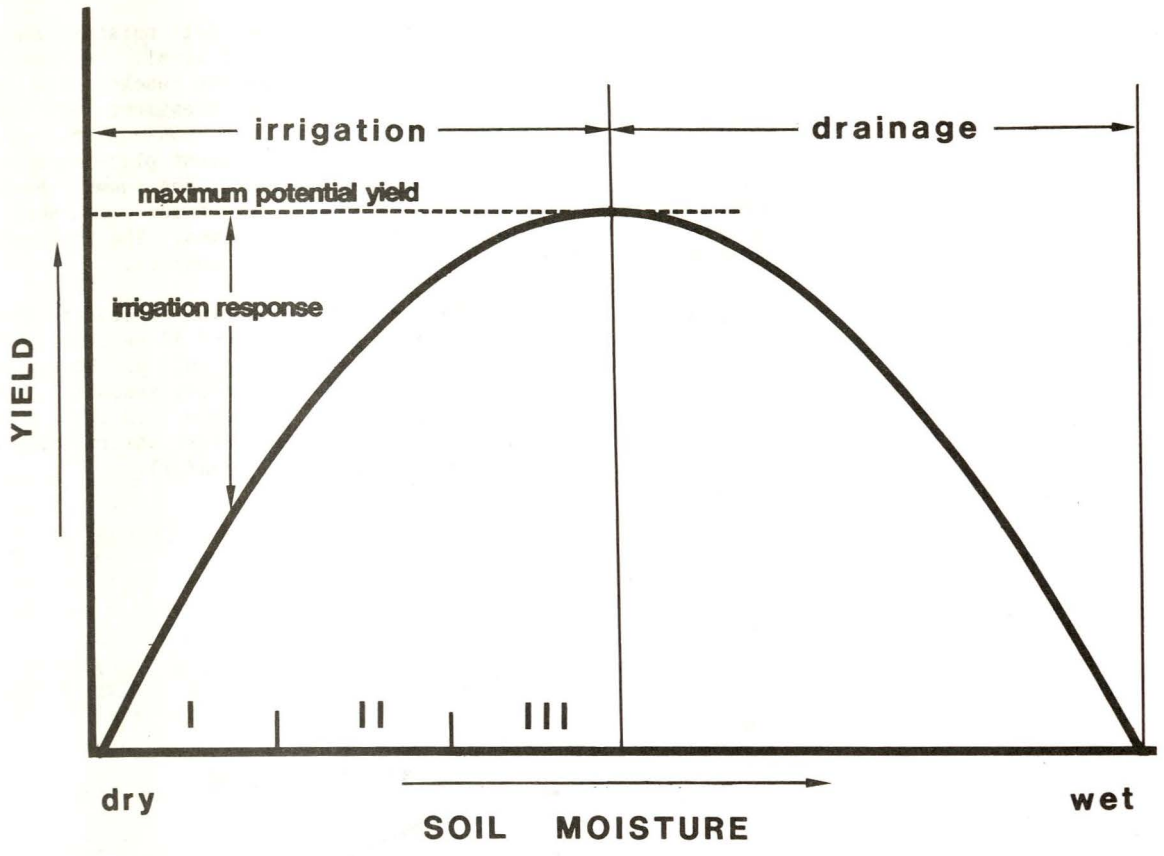


Figure 1.--Relation of tree yield (fiber or energy) to soil moisture. Irrigation (left half of the curve) can increase yield from the existing level, as illustrated by the curved line, up to the maximum potential yield. Drainage of the wet portion of the soil moisture spectrum can produce the same yield responses. Advantages of irrigation are classified into three categories:

Category I: create new commercial forest land.
Category II: increase probability (insurance) of producing a crop.
Category III: increase yield.

by classifying yield response into three arbitrary categories based on the value to a forest manager (fig. 1).

Category 1 represents very droughty soils where either there is no tree growth or the existing trees are noncommercial. Irrigating such land creates new commercial forest land. It is under these conditions that irrigation provides maximum gain in wood production.

Category 2 represents land capable of supporting forest without irrigation. However, chronic soil moisture deficits may substantially depress tree growth and infrequent droughts may result in substantial mortality or a crop failure. Irrigation under these conditions increases the probability of producing a commercial forest crop.

Category 3 represents land that is nearly certain of having sufficient soil moisture to produce a forest crop. Irrigation would slightly increase yields in most years.

The advantages of irrigation when viewed from this perspective are threefold. Increases in forest yield occur in all three categories, although the magnitude of increase differs greatly from one category to another. However, the important gains are that as sites become drier, irrigation has the added benefits of insuring that a crop will be obtained and creating new commercial forest land. The value of these latter two benefits would obviously differ by geographic area and by individual

wood users within an area.

Irrigation Effects on Yield

A review of more than 80 papers dealing with agronomic and horticultural crops concludes that yields are usually greatest with the wettest soil moisture regimes (Stanhill 1957). A review of forest irrigation indicates that irrigation usually increases tree growth (Hansen 1978). Even small decreases in soil moisture tension will increase the growth of forest trees (Zahner 1968). Irrigation research with hybrid poplars supports these conclusions. Preliminary results based on 3 years of irrigating hybrid poplar planted at 1 x 1 m spacing at Rhinelander, Wisconsin, show that irrigation consistently increased tree growth (fig. 2). In this study plots were irrigated whenever soil moisture reached the designated treatment level. For example, whenever the soil moisture reached -1.5 bar, the plots assigned that treatment were irrigated to field capacity. Consequently the wettest (-0.3 bar) treatment plots were irrigated 3 to 6 times during the summer whereas the drier (-1.5 bar) treatment plots were only irrigated 0 to 4 times. The "no-irrigation" plots served as a control.

The wettest irrigation treatment of -0.3 bar produced yields 76 and 44 percent greater than the unirrigated controls at the end of the second and third growing seasons, respectively (Table 1). The effect of irrigation on increased yield in weight was the same both years (about 1.5 t/ha/yr).

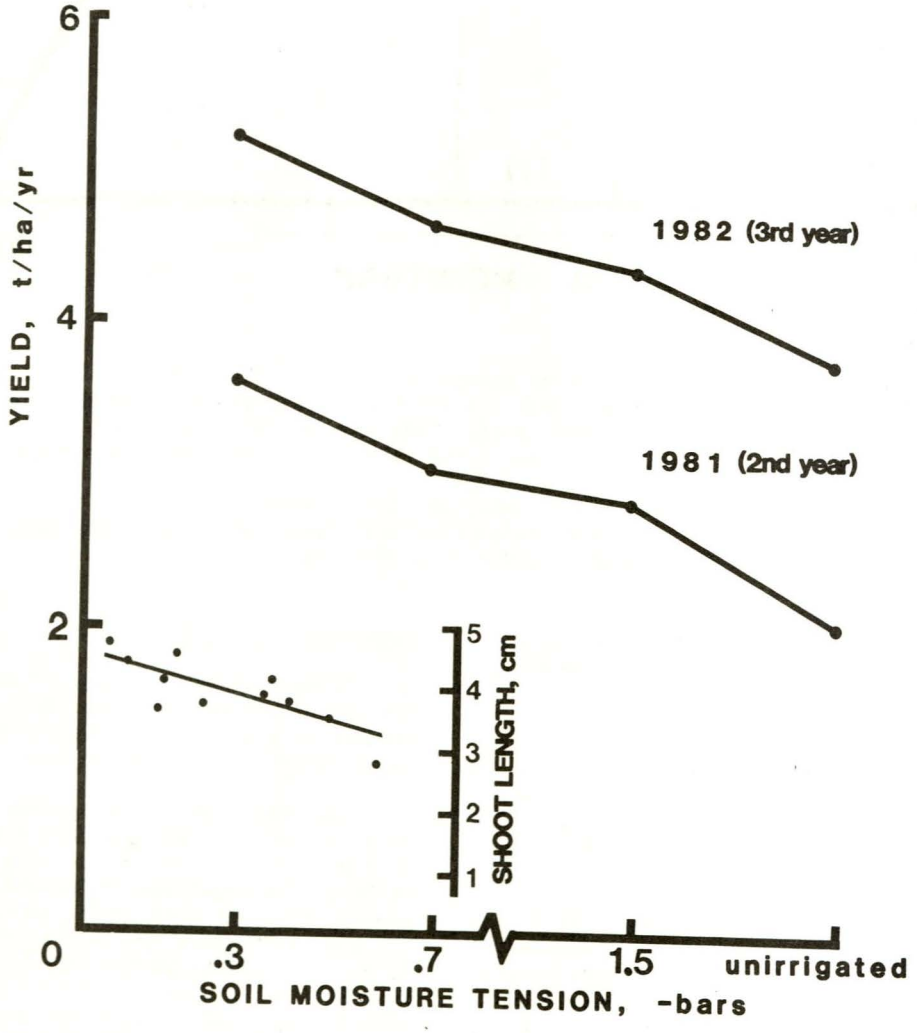


Figure 2.--Effects of soil moisture tension (irrigation) on 10 day shoot length and on 2nd and 3rd year yields.

Table 1.--Effect of irrigation on yield.

Year	Treatment: -0.3 bar	Treatment: not irrigated	yield increase	
	t/ha/yr			%
2	3.5	2.0	1.5	76
3	5.3	3.7	1.6	44

What Soil Moisture Tension is Best?

The same irrigation study showed that tree growth during a 3-year period was satisfactory under all irrigation treatment regimes including no irrigation, but tree growth was greatest with the highest irrigation treatment (fig. 2). Although the highest level of irrigation increased total aboveground yields by 44 to 76 percent, irrigation is not essential for growing trees on that site and so far has not been needed as insurance against infrequent drought. Consequently, this site would probably fall within Category 3 (or possibly 2) (fig. 1).

We investigated the effects of soil moisture tension from -0.6 bars to -0.05 bars on early growth of hybrid Populus hardwood cuttings in a growth room (Hansen and Phipps, in press). The soil moisture treatments were obtained by using boxes, each filled with soil at a different soil moisture tension. Unrooted cuttings were then placed in the boxes and we observed their early growth.

The results indicate that bud opening and shoot growth begins sooner as soil moisture tension decreases to at least-0.05 bar (fig. 2). The results of this growth room study together with the results of the field study indicate that the conclusions of Stanhill (1957) and Zahner (1968) also apply to hybrid poplar, i.e., yields are greatest with the wetter soil moisture regimes.

When to Irrigate?

It is sometimes argued that irrigation is most important during plantation establishment, because at this time drought might result in total failure of the plantation (Rose et. al. 1981). In contrast, absence of irrigation in older plantations presumably might only reduce growth but not affect survival, assuming that the plantation is established on a site of at least moderate quality. But is this the case? And how frequently might such conditions occur?

In 1981 we studied growing season soil moisture conditions under a newly established plantation and also under a 2-year-old plantation both with and without irrigation (fig. 3). Soil moisture stress reached higher tensions under the 2-year-old plantation. Irrigation did not produce significant differences in tree height growth in the new plantation but did produce significant biomass differences with the 2-year-old trees.

Rain during July and August of 1981 was well below average:

		July	August
Average precipitation	(mm)	3.53	4.27
1981 precipitation	(mm)	1.18	0.82

Despite this exceptionally low rainfall, the newly planted unirrigated plots survived and grew satisfactorily. Therefore, it appears that severe mid-to late-summer droughts do not prevent establishment of hybrid poplar plantations in northern Wisconsin.

These plots had good weed control. Soil moisture tensions in weedy plantations would be more severe. Also, drought in May or June might have a negative impact on survival. Both these factors might increase the need for irrigation during plantation establishment. On the other hand, soil moisture in northern Wisconsin is at field capacity in early spring, soil moisture can be conserved by good weed control, and cuttings can be soaked prior to planting to compensate for "dry" (-0.6 bar) soil moisture conditions (Hansen and Phipps, in press). These latter three factors decrease the possibility of encountering severe moisture problems in early spring when establishing plantations.

Although irrigation may in some cases be essential to establish a plantation, it appears that such instances are infrequent in northern Wisconsin.

Negative Effects of Irrigation

It is sometimes argued that irrigation will promote leaf diseases because of increased duration of leaf wetness (Rose et. al. 1981, Schipper 1976, Uriu and Magness 1967). However, the total duration of leaf wetness during a growing season is affected only to a very minor extent by irrigation. Typically, we irrigated on only 1 or 2 days per month whereas it rained on 8 to 15 days per month (table 2). Even in a very dry month rainy days outnumbered irrigation days by 2 to 1

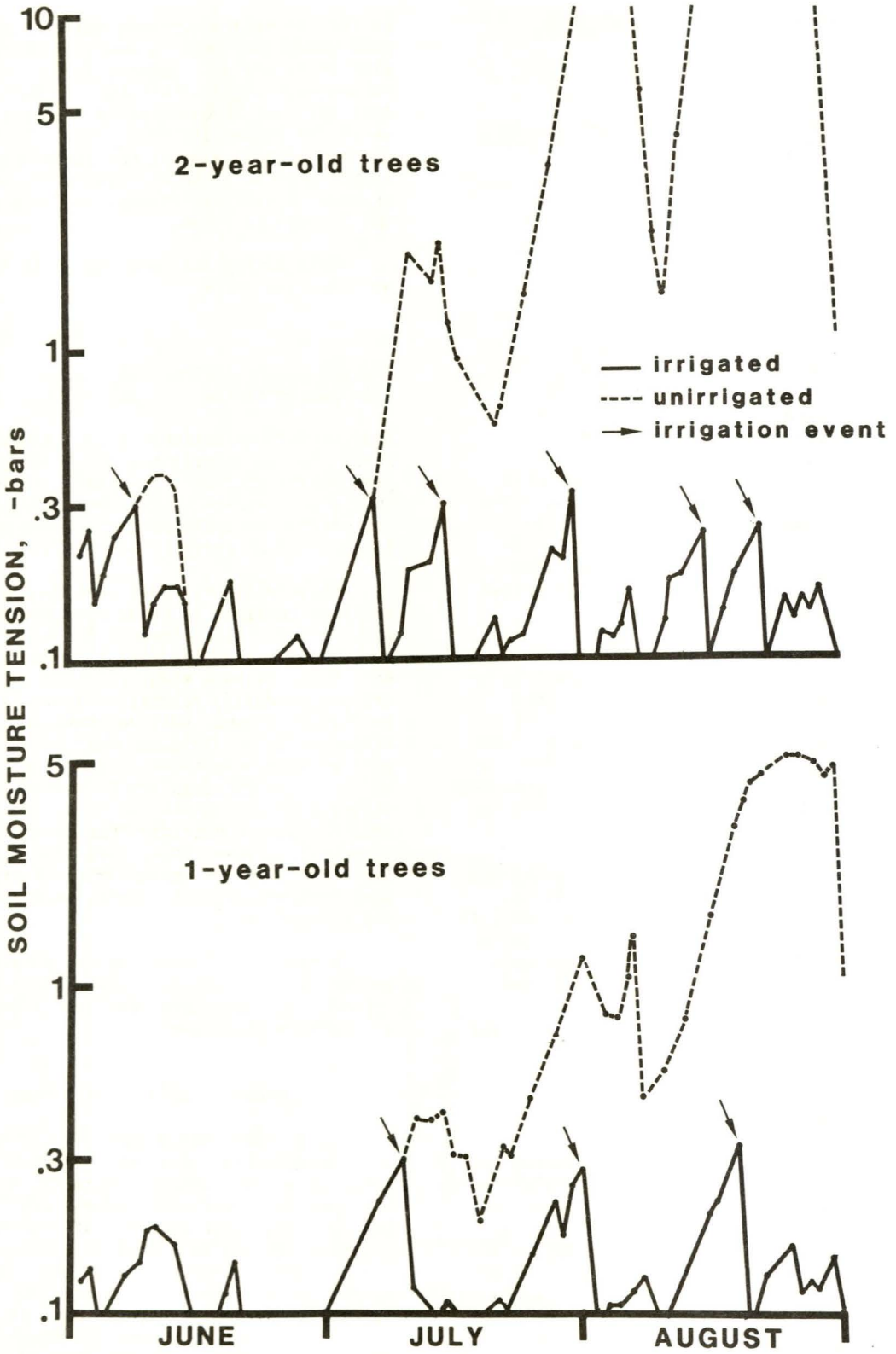


Figure 3.--Soil moisture tension trends under intensively cultured plantations with and without irrigation during the 1st and 2nd growing seasons. Irrigation was done when tensions reached -0.3 bar.

Table 2.--Comparison of the number of days per month with precipitation (P), or irrigation when soil moisture tension reached -0.3 bar ($I_{.3}$) or -0.7 bar ($I_{.7}$) during the first three growing seasons. Irrigation lasted less than 1 hour for a particular tree; precipitation typically lasted from one to several hours. Frequently it rained several times in 1 day, and occasionally it rained an entire day.

Month	1980			1981			1982		
	P	$I_{.3}$	$I_{.7}$	P	$I_{.3}$	$I_{.7}$	P	$I_{.3}$	$I_{.7}$
	days								
May	5	0	0	7	0	0	12	0	0
Jun	11	1	0	15	1	0	6	2	2
Jul	13	1	0	6	3	1	12	2	1
Aug	14	1	0	8	2	1	8	2	1
Total	43	3	0	36	6	2	38	6	4

when compared to the wettest irrigation regime (see July 1981 when only 1/3 of the normal monthly rain occurred). Even then only one irrigation was applied to the -0.7 bar treatment, which is a common soil moisture tension level in agronomic practice at which to irrigate. A maximum of 6 irrigation days in any one season compares with 36 to 42 rainy days in the same period.

An additional factor is that irrigation of a particular tree lasts less than an hour under our travelling gun system. In contrast, rain may last anywhere from a fraction of an hour to a day. Also, weather conditions associated with rainfall often minimize evaporation so that leaf surfaces remain wet for a long time. In contrast, irrigation is usually done when weather conditions are dry and leaves dry rapidly, thus minimizing duration of leaf wetness. The greatest number of irrigation days occur in dry years. Wet years may need no supplemental irrigation. Therefore, irrigation tends to bring leaf environmental conditions in dry years slightly closer to that experienced naturally in wet years.

Another factor to consider in addition to rain and irrigation is the occurrence of dew. Although we have no direct measurements of dew formation, relative humidity data can be used as an index of the presence of dew. During the June - August growing season, relative humidity reached 100 percent almost every night each of the 3 years and remained at 100 percent for generally 6 to 12 hours. Although relative humidity of 100 percent is not conclusive proof that dew occurred, it is supported by field observations that dew was present almost every night during the summer growing season and normally persisted until mid-morning of each day.

It appears that irrigation is a minor factor in increasing the frequency of leaf wetness during the growing season. It also seems unlikely that the duration of wetness from irrigation will exceed that of either rain or dew. Therefore, irrigation is probably not an important factor in the spread of tree diseases.

Discussion

Analyses conclude that irrigation is not economical for hybrid poplar SRIC plantations yielding 15 t/ha/yr (Rose et. al. 1981). And the yield used in these analyses has been reached only in two of our small research plots (Ek and Dawson 1976). Therefore, this yield could be considered a record. Boyer (1982) shows that average yields for grain crops are only 1/7 that of record yields. Crops such as potatoes and sugar beets with marketable vegetative structures have average yields about 1/3 that of the record yields. Therefore, it seems likely that the average yields of hybrid poplar will be much less than (perhaps half?) the 15 t/ha/yr achieved in our small research plots. Although further research in intensive culture will likely increase yields, it will probably be a long time before the present average yields increase to the levels of the record yields. Therefore, it is unlikely that irrigation will soon become economical when justified on average yields that may be achieved in the foreseeable future.

It does not seem likely that irrigation will be justified based on its need for establishing plantations. Our data show little need for irrigation during the year of plantation establishment, even during an exceptionally dry summer. Also, the establishment period is one of the few times when alternatives to irrigation are available for managing

soil moisture. Good weed control can substitute for irrigation and at a fraction of the cost. For example, post-planting weed control costs from $3.00 to $13.00/acre compared with irrigation costs of $100/acre for annual operation plus $43.00/acre fixed cost for equipment (Rose et. al. 1981).

Irrigation probably has little impact on the duration of leaf wetness during the growing season. Therefore, it seems likely that irrigation is not an important factor in the spread of tree diseases.

Irrigation has not been able to be economically justified based on its influence on woody biomass yields in the past, and it seems that justification based on further increases in yields will be difficult in the foreseeable future. Consequently, if irrigation is "to pay", it must do so on the basis of other benefits in addition to the documented favorable impact on yields. Additional justification for irrigation must rely to a large extent upon 1) the value of bringing new (previously unproductive) land into the highest levels of production and being able to locate such land near a mill, and 2) the insurance value of greatly reducing risks of growth or mortality losses directly from drought or from secondary attacks by insects and diseases thus assuring a stable fiber supply. Also to be considered is the value of using the land for wastewater disposal via irrigation. These factors must be considered in any determination of whether or not to irrigate, even though their consideration may be highly subjective. Although analyses have shown irrigation of SRIC plantations with a travelling gun system to be uneconomical when based on yields alone, other factors may make irrigation attractive to some large forest land holders.

LITERATURE CITED

Boyer, J. S. 1982. Plant productivity and environment. Science 218:443-448.

Ek, A. R. and D. H. Dawson. 1976. Actual and projected growth and yields of Populus 'Tristis #1' under intensive culture. Can. J. For. Res. 6:132-144.

Greenshields, Elco L. 1955. The expansion of irrigation in the west. In Water, The yearbook of Agriculture 1955. U.S. Government Printing Office, Superintendent of Documents. Washington 25, D.C. p. 247-251.

Hansen, Edward A. 1978. Forest irrigation: a review. In Proceedings, Soil moisture... site productivity symposium. Myrtle Beach, South Carolina, November 1-3, 1977. pp. 126-137.

Hansen, Edward A., David H. Dawson and David N. Tolsted. 1980. Irrigation of intensively cultured plantations with paper mill effluent. TAPPI 63(11):139-143.

Hansen, Edward A. and Howard M. Phipps. Effect of soil moisture tension and presoaking on early growth of hybrid Populus hardwood cuttings. Canadian Journal of Forest Research. (In press)

Mace, Arnett C. Jr., and Hans M. Gregersen. 1975. Evaluation of irrigation as an intensive cultural practice for forest crops. Iowa State Journal of Research, 49:305-312.

Marr, Paul D. 1967. The social context of irrigation. In Irrigation of agricultural lands. Robert M. Hagan, Howard R. Haise, Talcott W. Edminster and R. C. Dinauer, editors. Number 11 in the series of Agronomy, American Society of Agronomy, Publisher, Madison, Wisconsin. pp. 12-22.

Rose, Dietmar, Karen Ferguson, David C. Lothner and J. Zavitkovski. 1981. An economic and energy analysis of poplar intensive cultures in the Lake States. U.S. Department of Agriculture Forest Service, Research Paper NC-196, 44 p. U.S. Department of Agriculture Forest Service, Research Paper NC-196, 44 p. U.S. Department of Agriculture Forest Service, North Central Forest Experiment Station, St. Paul, Minnesota.

Rose, Dietmar W., and Robert D. Kallstrom. 1976. Economic feasibility of intensive culture. In Intensive plantation culture (five years research), p. 96-108. U.S. Department of Agriculture, Forest Service, General Technical Report NC-21, U.S. Department of Agriculture Forest Service, North Central Forest Experiment Station, St. Paul, Minnesota.

Schipper, Arthur L. Jr. 1976. Poplar plantation density influences foliage disease. In Intensive plantation culture (five years research), p. 81-84. U.S. Dept. of Agriculture, Forest Service, General Technical Report NC-21, U.S. Dept. of Agriculture Forest Service, North Central Forest Experiment Station, St. Paul, Minnesota.

Sheikh, Mahmood Iqbal. 1974. Optimum water requirement of shisham Dalbergia Sissoo - second assessment. The Pakistan Journal of Forestry 24(1):1-9.

Stanhill, G. 1957. The effect of differences in soil-moisture status on plant growth: a review and analysis of soil moisture regime experiments. Soil Sci. 84(3):205-214.

Tharp, Max M. and C. W. Crickman. 1955. Supplemental irrigation in humid regions. In Water, The yearbook of agriculture 1955. U.S. Government Printing Office, Superintendent of Documents, Washington 25, D.C. p. 252-258.

Uriu, K. and J. R. Magness. 1967. Deciduous tree fruit and nuts. In Irrigation of agricultural lands. Robert M. Hagan, Howard R. Haise, Talcott W. Edminster and R. C. Dinauer, editors. Number 11 in the series of Agronomy, American Society of Agronomy, Publisher, Madison, Wisconsin pp. 686-703.

Zahner, R. 1968. Water deficits and growth of trees. In Water deficits and plant growth II. (T. T. Kozlowski, ed.) Academic Press, New York. pp. 191-254.

EFFECT OF HARVESTING SEASON ON HYBRID POPLAR COPPICING

by

Terry F. Strong and Jerry Zavitkovski

Abstract.--A study was begun in 1980 in a 4-year-old planting of P. nigra var. betulifolia x P. trichocarpa to identify the effects of harvesting season on coppice production. Parts of the plantation were harvested monthly from October 1980 to September 1981. The trees were cut leaving 10 and 30 cm (4 and 12 in) stumps. Coppice measurements were taken 1 year after harvest. Harvesting during the leafless season (October to mid May) positively affected (a) stump survival, (b) height and d.b.h. growth of dominant sprouts, and (c) number of live sprouts/stump taller than 1.37m. Harvesting during the growing season discouraged coppicing. Stump height had no effect on stump survival or growth of dominant sprouts. However, stump height positively affected number of sprouts/stump. Therefore, to concentrate growth on a few sprouts, the stumps should be kept short. The 10 cm (4 in) stumps proved adequate.

In their review of factors influencing coppicing, Blake and Raitanen (1981) state that where species exhibit a seasonal variation in coppicing, sprouting is usually maximal when trees are cut in winter and minimal when they are cut in mid-summer. With some caution, the same generalization could be made about hybrid poplar coppicing. Good coppicing and coppice growth followed dormant season harvest of eastern cottonwood (DeBell and Alford 1972), various P. x euramericana clones (Lee and McNabb 1979), and P. 'Tristis #1' (Strong and Zavitkovski 1982). Poor coppicing followed growing season harvest in those studies. However, Anderson's (1979 b) studies, although consistent with the above results for P. x euramericana (clone I-45/51), showed that some aspen-type clones had good tolerance to growing season (July or August) harvesting. Obviously, poplar clones may respond differently to the season of harvest and each clone should be tested separately to determine its optimum harvesting time. Such knowledge may substantially increase the yield of the subsequent poplar coppice.

The objective of this study was to assess the effect of harvesting time on coppicing of clone NE-299 (NC-5331), a hybrid between P. nigra var. betulifolia x P. trichocarpa. The specific objectives were to establish between season of harvesting and (a) stump survival, (b) number of shoots per stump, and (c) height and d.b.h. growth of the dominant sprouts 1 year after the harvest.

MATERIALS AND METHODS

The study was conducted in a 4-year-old 0.25 ha plantation of NE-299 (NC-5331) established at 1.2 x 1.2 m (4 x 4 ft) spacing at the Harshaw Forestry Research Farm near Rhinelander, Wisconsin. The plantation was divided into 2 replications. Within each replication we staked out 12 plots, each with 55 trees (5 rows with 11 trees each). The plot size was 6 x 13 1/2 m (20 x 44 ft).

The sequence of cutting was randomized within each replication. One plot in each replication was cut in the middle of every month from October 1980 to September 1981. Three rows were harvested leaving a 30 cm (1 ft) stump and 2 rows were harvested leaving a 10cm (4 in) stump. At the time of harvest, we recorded the diameter of the stump at the cut surface.

Coppice measurements were taken 1 year after harvest or, for trees harvested during the dormant season, any time during the following dormant season. The following data were recorded:

(a) number of living stumps,

(b) height of the dominant sprout on each stump,

(c) d.b.h. of the dominant sprout on each stump, and

(d) number of live sprouts/stump taller than 1.37 m.

We analyzed the data by means of analysis of variance and regression analysis, and we tested the significance of specific comparisons by a "t" test with a confidence level of 95%.

RESULTS AND DISCUSSION

Physiologically, October and May are not dormant season months. However, we found no significant difference between harvest months within the October to May period in stump survival, number of sprouts/stump, and height and d.b.h. growth. Therefore, we pooled the data for that period (called dormant season in this paper). Although stump survival following the September harvest did not differ from that of dormant season harvesting, number of sprouts, height, and d.b.h. were substantially smaller. Growing season harvesting, June through August, was the least productive and had the lowest stump survival.

Stump Survival

The average stump survival was 92% for the September through May harvests (table 1). It was 65% for the June harvest and less than 10% for the July and August harvests. Stump survival for the growing season harvests was lower than the 62% found in the previous study with P. 'Tristis #1' (Strong and Zavitkovski 1982).

harvested in July, August, and September. Whereas the July and August harvests were followed by low to intermediate stump survival (except for P. canescens cl. 'Ingolstadt' whose stump survival was 90 to 100% in all 3 months of testing), stump survival following the September harvest was 100% in three clones and 80 to 30%, respectively, for the other two clones. Such results are more typical of a dormant season month. However, based on height and d.b.h. growth reached in our study, September could be classified as a growing season month. Perhaps more appropriately, September is a transition month that may have dormant or growing season characteristics depending on the weather preceding the harvest.

Height of Dominant Sprouts

The average height of the dominant sprouts ranged from 0.9 for the June-August harvests to 2.3 m for the dormant season harvests (table 1). In a previous study with P. 'Tristis #1' (Strong and Zavitkovski 1982), the respective heights were 0.9 and 1.6 m. The ratio between the dormant season and growing season heights was 2.6 in the present study and 1.8 in the previous study. This compares with a ratio of 1.7 obtained by DeBell and Alford (1972) in a study with P. deltoides in Mississippi.

First year average height of the dominant sprouts developing after the dormant season harvesting, 2.3 m, was similar to heights reported by Anderson (1979 a) for clone 1-45/51 in Ontario

Table 1.--Effect of harvesting season on stump survival and coppice development of poplar hybrid NE-299 (NC-5331)

Month	Stump survival			Growth of dominant sprouts						Number of sprouts[1/]		
				Height			d.b.h.					
	Mean	SD	N[2/]	Mean	SD	N	Mean	SD	N	Mean	SD	N
	(%)			(m)			(cm)					
October to May	92[a]	8	32	2.3	0.4	294	0.9	0.2	293	7.5	3.7	293
September	93[a]	5	4	1.5	0.3	34	0.5	0.1	25	3.4	2.3	25
June	65[b]	10	4	0.9	0.3	26	0.6	-	1	2.0	-	1
July	9[c]	11	4	0.7	0.1	3	-	-	-	-	-	-
August	5[c]	10	4	1.1	0.2	2	-	-	-	-	-	-

1/ Sprouts taller than breast height (1.37 m).
2/ Number of observations

It is difficult to classify September either as a growing season or dormant season month. Stump survival following September harvesting was typical of that achieved in dormant season harvesting. A similar conclusion could be drawn from Anderson's (1979 b) studies with five different poplar clones (ranging from 1.96 to 2.04m) , Crist et al (appears elsewhere in this publication) for P. 'Tristis #1' in Rhinelander (ranging from 1.84 to 2.19m), and Zavitkovski (1982) for various northeastern (2.46m) and P. x euramericana clones (2.27m).

Diameter of Dominant Sprouts

The average d.b.h. of dominant sprouts of individuals harvested during the dormant season was 0.9 cm and that resulting from the September harvest 0.5 cm (table 1). Only one dominant sprout reached breast height (1.37 m) following the growing season (June to August) harvest. In our previous study with P. 'Tristis #1' (Strong and Zavitkovski 1982), the average dominant sprout d.b.h. following the dormant season harvest was 0.93 cm. Anderson (1979 a) reported average d.b.h.'s of winter harvested 1-45/51 ranging from 0.94 to 0.97 cm. Although the average d.b.h. of winter-harvested eastern cottonwood (DeBell and Alford 1972) was substantially greater than achieved in our study, the same principle of less growth after the growing season harvest applied.

Season of Harvest and Number of Sprouts/Stump

The average number of sprouts taller than 1.37 m (breast height) was 7.5 for stumps of trees harvested during the dormant season and 3.4 for those harvested in September (table 1). Only one sprout taller than 1.37 m was produced following the June to August harvest. In the previous study with P. 'Tristis #1' (Strong and Zavitkovski 1982), an average of 2.5 sprouts/stump taller than breast height developed after the dormant season harvest. and winter harvested eastern cottonwood in Mississippi (DeBell and Alford 1972) produced an average of 5.3 sprouts/stump taller than breast height.

Stump Size and Coppicing

Stump height had little effect on stump survival or height of dominant sprout. Dominant sprouts originating from 30-cm stumps were only slightly larger in diameter than those origninating from 10-cm stumps (table 2). However, stump height had a substantial effect on number of sprouts/stump. The 30-cm stumps had 8.8 sprouts/stump and the 10-cm stumps 6.2 sprouts. Similar findings were reported by Crist et al. (appears elsewhere in this publication) for P. 'Tristis #1' and Belander (1979) for sycamore. Both noted that several years after harvest, number of sprouts/stump tended to equalize

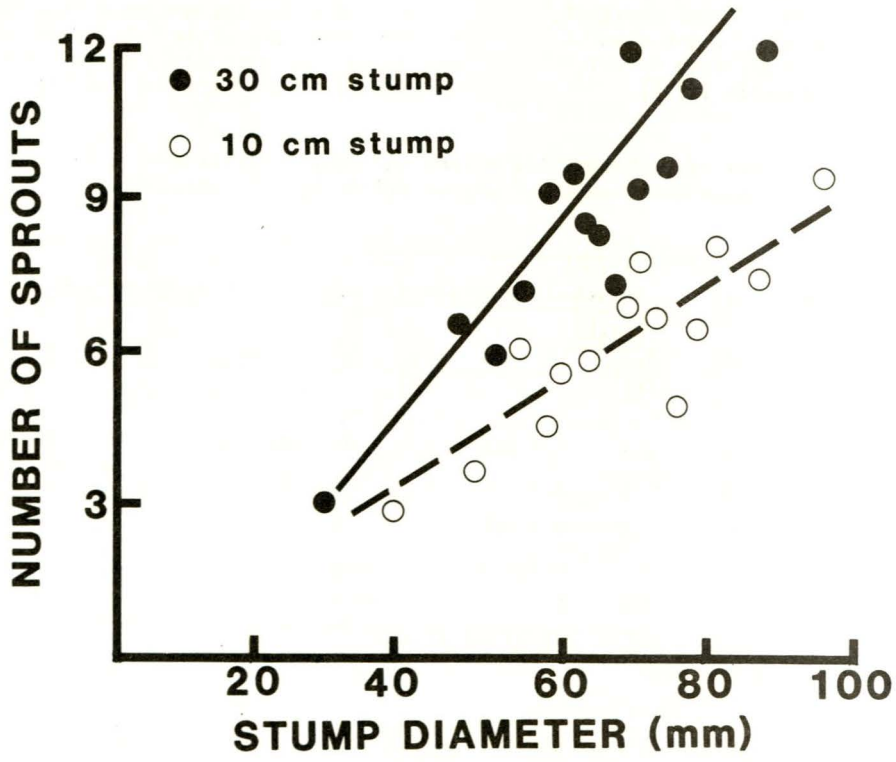


Figure 1.--Relation Between Stump Diameter and Number of Sprouts/Stump for 10-and 30-cm Stumps

due to sprout mortality. In a similar study with eastern cottonwood, DeBell and Alford (1972) found no significant difference due to stump height in number of sprouts/stump or diameter and height growth of sprouts.

Table 2.--Effect of stump height on coppice development

Stump Height	Coppice Development		
	Height	d.b.h.	Sprouts/Stump
(cm)	(m)	(cm)	(Number)
30	2.19	0.98	8.8
10	2.11	0.89	0.2
F-ratio	1.73	10.34*	40.97*

*Significant at the 95% confidence level.

Number of sprouts/stump was also positively related to stump diameter at the cut surface (fig. 1). Belanger (1979) reported similar relations for sycamore and we noted a similar trend in our studies with P. 'Tristis #1' (Strong and Zavitkovski 1982).

CONCLUSIONS

1. Dormant season harvest (October to May) of hybrid poplar NE-299 (NC-5331) positively affected (a) stump survival, (b) height and d.b.h. of dominant sprouts, and (c) number of sprouts/stump.

2. Dormant season harvesting is strongly recommended to maximize coppice production in the Lake States.

3. July-August is the best harvesting time to discourage sprouting.

4. Stump height positively affected number of sprouts/stump.

Therefore, to concentrate growth on a few sprouts, the stumps should be kept short. Here, stumps 10 cm (4 in) in height proved adequate. To encourage number of sprouts for cutting production, cut higher (30 cm).

ACKNOWLEDGMENT

We thank Drs. T. J. Blake and Neil Nelson for their review of this manuscript.

LITERATURE CITED

Anderson, H. W. Biomass production of hybrid poplar grown in minirotation. In: Poplar research, management and utilization in Canada, D.C.F. Fayle, L. Zsuffa, and H. W. Anderson (eds.), p. 11-1 to 11-13. Forest Res. Info. Paper 102; Ministry Nat. Res., Ontario. 1979 a.

Anderson, H. W. Poplar farming. In: Poplar research, management, and utilization in Canada. D.C.F. Fayle, L. Zsuffa, and H. W. Anderson (eds.), p. 3-1 to 3-10. Forest Res. Info. Paper 102; Ministry Nat. Res., Ontario. 1979 b.

Belanger, Roger P. Stump management increases coppice yield of sycamore. Southern J. Applied Forestry 3(3); 101-103. 1979.

Blake, T. J., Raitanen W. E. A summary of factors influencing coppicing. In: International Energy Agency, Programme of Research, Development and Demonstration on Forestry Energy, Planning Group B., T. J. Blake and W. E. Raitanen (eds.), IEA Report NE 1981: 22; 24 p.; 1981.

DeBell, Dean S., Alford, Lee T. Sprouting characteristics and cutting practices evaluated for cottonwood. Tree Planters' Notes 4(23): 1-3. 1972.

Lee, Don Koo, McNabb, Harold S. Biomass production in coppiced hybrid poplar plantations as influenced by stump height, season of cutting, and number of seasons of growth at Ames and Rhinelander plantations. Unpublished report on file at the Forestry Sciences Laboratory, Rhinelander, WI, 10 p. 1979.

Strong, Terry F., Zavitkovski, J. Harvesting season affects regeneration and growth of Populus 'Tristis #1' coppice. In: 19th Annual Meeting of North American Poplar Council, Rhinelander, WI, Jerry Zavitkovski and Edward A. Hansen (eds.), Kansas State Univ. Press, Manhattan, KS, p. 94-102. 1982.

Zavitkovski, J. Juvenile coppice growth and production of several hybrid poplars in northern Wisconsin. In: 19th Annual Meeting of North American Poplar Council, Rhinelander, WI. Kansas State Univ. Press, Manhattan, KS, p.102-112. 1982.

EFFECT OF SEVERING METHOD AND STUMP HEIGHT ON COPPICE GROWTH

John B. Crist[1]

James A. Mattson[2]

Sharon A. Winsauer[3]

Abstract.--In this study we evaluated the effect of stem severing method and stump height on coppice growth in a short-rotation intensively cultured Populus plantation 1, 2, and 3 years after cutting. Initially, stumps 46 cm high had smaller and significantly more sprouts than either 8 or 15 cm high stumps. However, the dominant sprouts were not affected by the stump height. After subsequent growing seasons, the dominant sprouts were the only ones to survive, and no effect of stump height was present. Severing method--shearing or chain sawing--did not affect coppicing as long as the stumps were not excessively damaged during the original harvest.

Short-rotation intensive culture (SRIC) of trees is a promising way to increase wood biomass productivity (U.S. Department of Agriculture, Forest Service 1980). The Populus genus has been shown to be extremely productive under SRIC and to be good raw material for reconstituted forest products.

Either rooted or unrooted poplar cuttings are usually planted for the first rotation of a SRIC plantation. Subsequent rotations result from coppice sprouts regenerating from the stumps that remain after the first harvest and from short sprout stubs after coppice rotations (International Energy Agency 1981). However, little information is available on the effect of stem severing method and stump height on subsequent coppice growth.

The objectives of this study were to evaluate the effect of two methods of severing trees--sawing and shearing--and three residual stump heights--8, 15, and 46 cm (3, 6, and 18 inches)--on the number of coppice sprouts per stump, average sprout height and diameter, and dominant sprout height and diameter.

[1]Field Representative, USDA, Forest Service, Resource Use Staff, State and Private Forestry, Morgantown, WV.

[2]Supervisory Mechanical Engineer, USDA Forest Service, No. Cent. Forest Experiment Station, Forestry Sciences Laboratory, Houghton, MI.

[3]Mathematician, USDA Forest Service, No. Cent. Forest Experiment Station, Forestry Sciences Laboratory, Houghton, MI

MATERIAL AND METHODS

Populus 'Tristis #1' trees (P. tristis x P. balsamifera) were grown at the Hugo Sauer Nursery near Rhinelander, Wisconsin. The plot was cultivated, fertilized, and irrigated to maintain optimum growing conditions for 6 years at a 0.6- by 0.6-m (2- by 2-ft) spacing; it had 36 rows of 12 trees each, for a total of 432 trees. However, at the harvest the plot contained only 315 trees because some trees had died and some had been removed for biomass determinations. At harvest, nonborder trees averaged 7.2 m (23.6 ft) in height and 5.6 cm (2.2 in) in diameter measured at 0.3 m (1 ft) above ground.

The trees were harvested during the dormant season (February 24, 1979) by either sawing or shearing. The sawing was done with a chain saw, and the shearing was done with a thin-bladed shear. The stems were severed at three heights, 8, 15, and 46 cm. These stump heights were chosen to include a practical range for mechanized harvesting equipment (8 and 15 cm) and one that might be necessary under heavy snow conditions (46 cm).

The six treatment combinations were used in a factorial experiment. We used a randomized complete block design with two replications. Standard analysis of variance techniques were used to evaluate the effect of stump height, severing method, and replication on the measured output variables. The total subplot area of each treatment was harvested by the prescribed method, and four adjacent nonborder stumps within each treatment were designated for subsequent coppice measurement.

After each of the first three growing seasons, all sprouts longer than 0.3 m (1 ft) were measured on each of 48 stumps (4 stumps/treatment x 6 treatments x 2 replications). The measurements were: total number of sprouts/stump, height (length) of each sprout from point of attachment to its tip, and diameter of each sprout measured at 0.3 m (1 ft) from point of attachment.

RESULTS AND DISCUSSION

Mortality

The method of severing the stems initially affected coppice sprout mortality. Five of the 48 stumps on which coppice growth was measured (24 sawn and 24 sheared) died before the first growing season. All of these dead stumps had been sheared. Although the stumps could have been killed by the shearing action itself, death was probably caused by physical damage inflicted during positioning of the shear. The shear used in this study was for larger trees and was so large that when one stump was being severed, its neighbors were occasionally damaged. The five stumps that died were also much smaller than average (2.4- to 4.7-cm stump diameters), which may have made them more susceptible to damage by the shear.

Two more stumps died, one sawn and one sheared, after the second growing season. These two stumps were also small (1.8 and 2.8 cm in diameter), and their death was probably due to increasing competition and not mechanical damage. In our opinion, the damage to residual stumps could be greatly reduced or eliminated by designing special harvesters for small trees grown in closely spaced plantations. (Mattson et al. in this proceedings). Recent data indicate that wider spacings may be more economically feasible for SRIC systems (Rose and DeBell 1978). Wider spacings would also reduce damage by allowing more area for harvesters to operate. A rectangular spacing with wider between-row spacing and closer within-row spacing could also be used to facilitate harvesting.

Number of Sprouts per Stump

After the first two growing seasons, residual stump height affected the number of coppice sprouts per stump (table 1). The shortest stumps (8 and 15 cm) had significantly fewer sprouts than the tallest stumps (46 cm). However, sprout numbers were not significantly different between the 8 and 15 cm stumps. These results were expected because shorter stumps have less surface area for originating sprouts.

By the third growing season, the number of sprouts per stump was significantly less. The average number of sprouts had decreased from 13 to 3 and no effect of stump height remained (fig. 1). This decrease was expected because competition between the sprouts caused the weaker sprouts to die back. Similar to the results reported by DeBell and Alford (1972), the point of attachment of the surviving sprouts after three growing seasons was always on the top portion of the residual stump (fig. 2). This indicates that no advantage is gained by leaving higher stumps. In fact, the higher stumps could increase the possibility of stump decay in later years. Severing method did not significantly affect the number of sprouts per stump.

Average Sprout Height and Diameter

Residual stump height also initially affected both average coppice sprout height and diameter (fig. 3). For the first 2 years the 8- and 15-cm stumps had significantly taller sprouts of larger diameter than the 46 cm stumps. But average sprout height and diameter between the 8- and 15-cm stumps were not signifiantly different.

These results may have a logical physiological explanation. Assuming each residual root system has equal or similar amounts of stored photosynthate (or energy), then the sprouts on the shorter stumps may receive more energy for early growth because of the fewer sprouts on the shorter stumps. Also, because the stumps themselves utilize part of the stored energy for respiration and growth, the taller stumps would require more energy than the shorter stumps, leaving less energy available for coppice growth on the taller stumps. Severing method did not significantly affect average sprout height or diameter.

Height and Diameter Of Tallest Sprouts

Neither residual stump height nor severing method significantly affected the height of the tallest sprout on each stump (fig. 4). These results appear to conflict with the previous explanation for the differences observed in average sprout height and diameter. However, when the sprouts develop their first leaves, they cease to be sinks for stored photosynthate from the root system and begin to be sources of photosynthate. Because the tallest sprouts are dominant, they produce more photosynthate than other sprouts on the same stump and photosynthate can be used to accelerate height growth. The original effect of stump height becomes masked by the rapid height growth of these dominant sprouts.

Table 1.--Effects of stump height and severing method on growth of SRIC Populus 'Tristis #1'coppice.

Severing Method and stump height	Year	Number of stumps	Average of all sprouts: Number	Height	Diameter	Average of tallest sprouts: Height	Diameter
				cm	cm	cm	cm
Sawn:							
8 cm	1	8	11.1 (4.8)[1]	119 (20.4)	0.88 (.20)	190 (36.9)	1.52 (.34)
	2	8	8.8 (3.4)	201 (48.7)	1.22 (.32)	390 (118.0)	2.40 (.84)
	3	7	3.9 (2.0)	371 (83.4)	2.24 (.62)	483 (46.9)	3.07 (.67)
15 cm	1	8	9.9 (3.6)	125 (15.8)	.92 (.13)	219 (20.9)	1.70 (.19)
	2	8	7.5 (3.4)	213 (39.1)	1.33 (.27)	446 (57.6)	2.90 (.64)
	3	8	2.2 (.89)	424 (82.7)	2.78 (.65)	496 (81.1)	3.43 (.99)
46 cm	1	8	13.6 (2.8)	116 (15.0)	.76 (.14)	208 (17.8)	1.50 (.21)
	2	8	11.0 (3.9)	182 (35.2)	1.06 (.22)	427 (36.4)	2.80 (.56)
	3	8	3.5 (.93)	342 (43.1)	2.06 (.36)	488 (50.2)	3.42 (.92)
Sheared:							
8 cm	1	6	8.3 (3.6)	118 (18.7)	1.0 (.15)	196 (27.2)	1.84 (.23)
	2	6	6.0 (3.3)	239 (34.8)	1.66 (.26)	446 (63.4)	3.40 (.50)
	3	6	3.0 (1.8)	387 (54.6)	2.82 (.33)	518 (75.3)	4.23 (.73)
15 cm	1	5	14.0 (8.5)	120 (15.4)	.89 (.19)	207 (44.0)	1.63 (.20)
	2	5	12.0 (6.7)	202 (51.7)	1.26 (.29)	417 (50.7)	2.80 (.84)
	3	5	4.2 (2.2)	352 (65.4)	2.27 (.61)	470 (74.2)	3.48 (1.2)
46 cm	1	8	20.1 (9.1)	98 (15.1)	.68 (.10)	184 (34.0)	1.42 (.32)
	2	8	14.9 (7.2)	160 (26.6)	.95 (.17)	402 (107.0)	2.70 (.87)
	3	7	4.0 (1.0)	361 (30.0)	2.33 (.31)	499 (44.0)	3.90 (.75)

[1]Entries are average values for the given number of stumps (observations). Number in parentheses is the standard deviation.

After three growing seasons, the dominant sprouts have clearly emerged. Of the 41 living stumps, 37 had from 1 to 3 sprouts that were taller than 400 cm. These dominant sprouts were similar in height and diameter. The taller sprouts were also usually the larger in diameter and vice versa. Of the 41 tallest sprouts, 37 were also the largest in diameter.

CONCLUSIONS AND RECOMMENDATIONS

Stump height initially affected the number of coppice sprouts per stump and average sprout height and diameter. However, after only three growing seasons, the smaller, weaker sprouts had already become victims of competition and from one to three dominant sprouts had emerged. We expect these dominant sprouts to survive despite the increasing competition. Each stump, regardless of its height or how it was severed, would have from one to three sprouts containing nearly all of the areal portions of biomass in the plot. We recommend not leaving high stumps unless deep snow conditions during harvest require it because they lose more biomass and have a higher possibility of stump decay than short stumps. Severing method did not affect the sprouting of the stumps unless they were severely damaged during harvesting.

LITERATURE CITED

DeBell, Dean S., Lee T. Alford. 1972. Sprouting characteristics and cutting practices evaluated for cottonwood. Tree Planters' Notes 23(4): 1-3.

International Energy Agency. 1981. A summary of factors influencing coppicing. IEA Report from planning Group B NE1981:22. In: Blake, J.T.; W. E. Raitanen, eds. Stockholm Sweden. National Swedish Board for Energy Source Development. 24 p.

Rose, Dietmar, Dean S. DeBell. 1978. Economic assessment of intensive culture of short-rotation hardwood crops. J. For. 76(11): 706-711.

U. S. Department of Agriculture, Forest Service. 1980. Energy & wood from intensively cultured plantations: research and development program. Gen. Tech. Rep. NC-58, St. Paul, MN. U.S. Department of Agriculture, Forest Service, North Central Forest Experiment Station. 28 p.

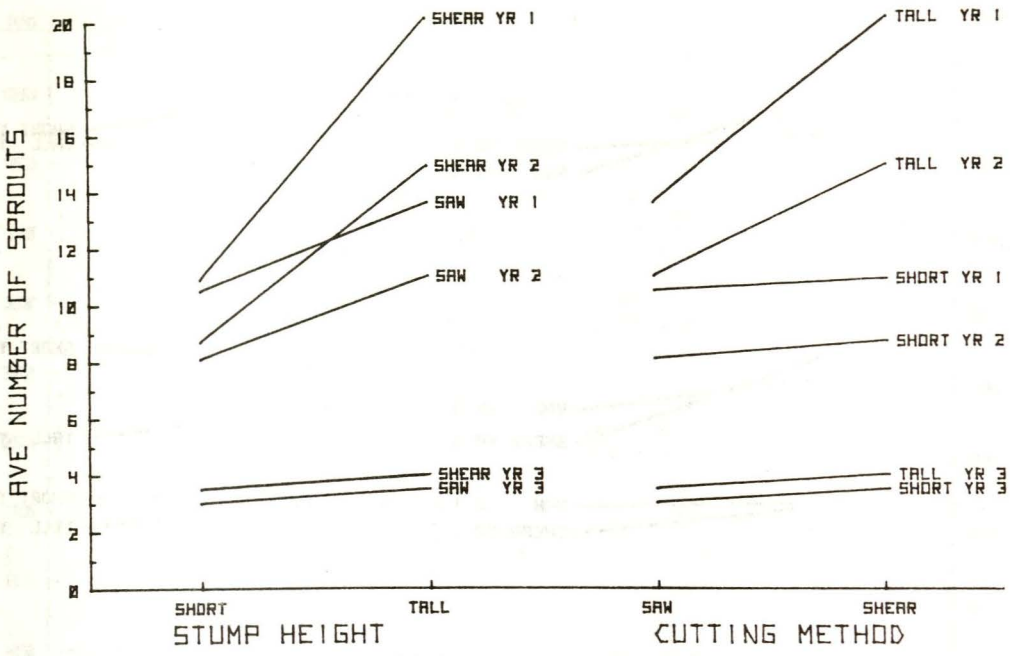


Figure 1.--Average number of spouts per stump for Populus 'Tristis #1' coppice by cutting method and stump height 1, 2, and 3 years after harvest.

Figure 2.--Typical sprouting on 46 cm high Populus 'Tristis #1' stumps after three growing seasons.

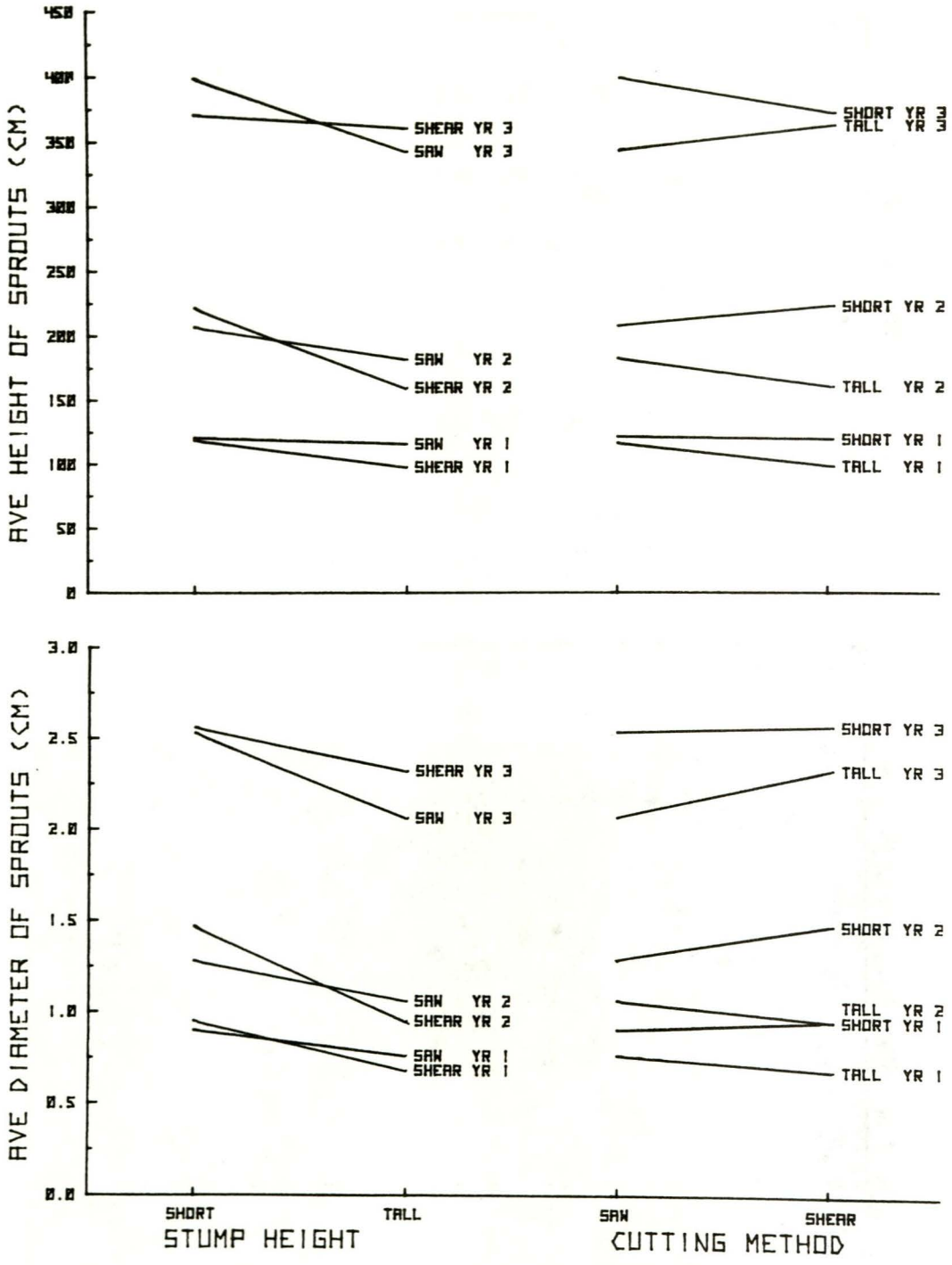


Figure 3.--Average sprout height and diameter for Populus 'Tristis #1' coppice by cutting method and stump height 1, 2, and 3 years after harvest.

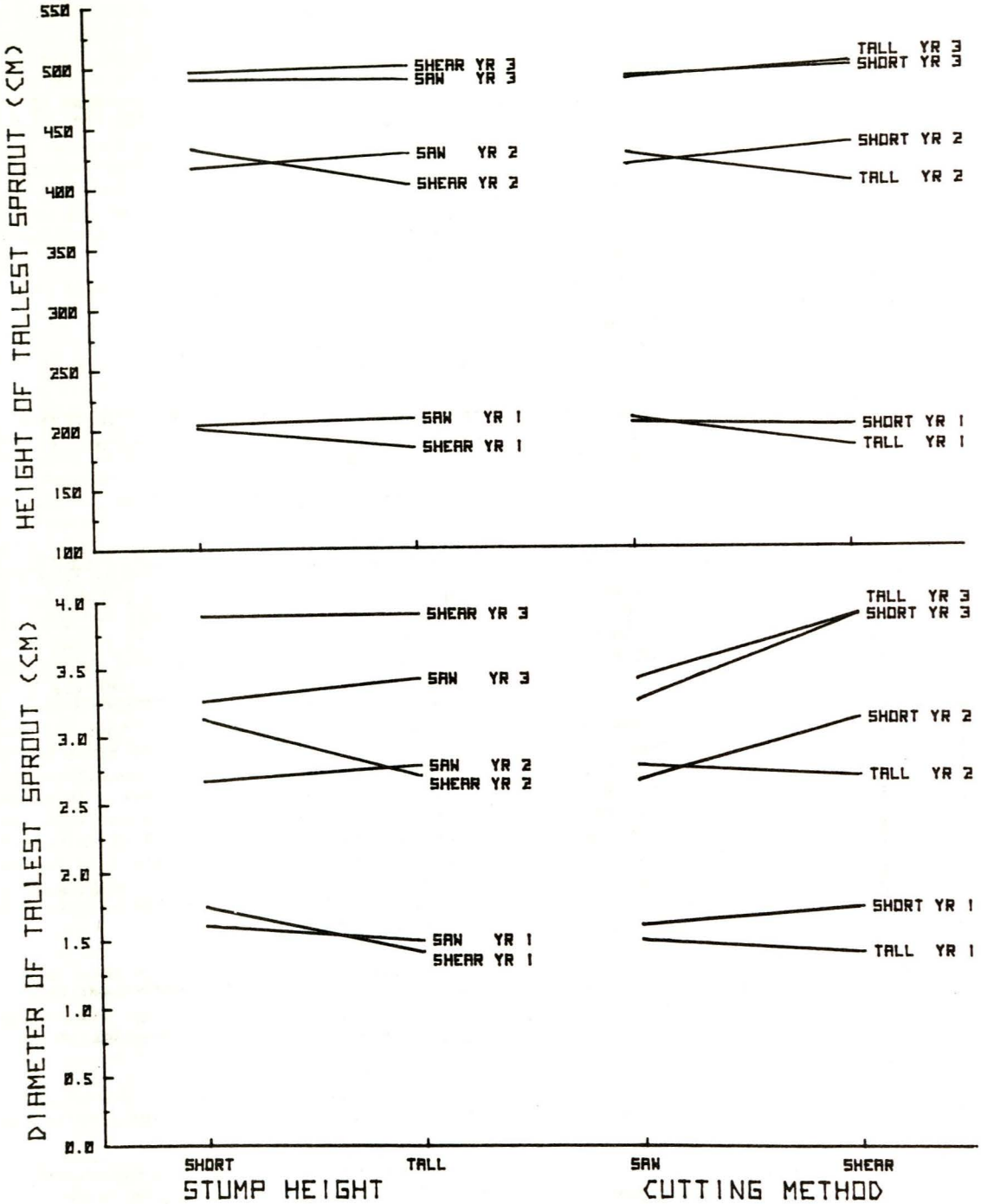


Figure 4.--Height and diameter of tallest sprouts for Populus 'Tristis #1' coppice by cutting method and stump height 1, 2, and 3 years after harvest.

GROWTH AND YIELD OF *POPULUS* COPPICE STANDS GROWN UNDER INTENSIVE CULTURE[1/]

Alan R. Ek, John E. Lenarz, and Albert Dudek[2/]

Abstract.--Growth and survival data on the first three years of development of coppiced stands representing seven clones are described. The data were collected from small multispaced plots at the Rhinelander, Wisconsin, nursery. Sprout growth and mortality equations developed from this data were then integrated with growth and mortality equations developed for older trees of cutting origin to form a simulation model of coppice stand development. Model output suggests potential yields of 5-15 metric tons per hectare per year can be achieved at ages 5-15 years from a variety of spacing and clone combinations under intensive culture. However, there was evidence of considerable variability in results within clones.

Coppicing is a potentially attractive option for short rotation intensive culture (SRIC) of *Populus*. This study was an attempt to estimate that potential for seven clones. The primary objective was to quantify the relationship of coppice stand development to parent stand (before coppice) spacing.

Little information on coppicing was available for the clones considered in this study. Ek and Brodie (1975) presented results for natural aspen stands, primarily *Populus tremuloides* stands. They found site quality, parent and residual stand basal area, season of cutting and cutting treatment had important effects on aspen sucker density. DeBell and Alford (1972) found that stump height and angle of cut had no significant effect on the vigor, size, or number of sprouts produced by *Populus deltoides*. Season of cutting, however, had a significant effect on the number and sizes of sprouts. Stumps cut from September to March produced significantly more sprouts than those cut during the growing season. These authors also noted that stump age may affect vigor and mortality of the sprouts produced. Younger stumps tend to produce sprouts from dormant buds, while sprouts from advantitious buds were prevalent on older stumps. Sprouts from advantitious buds tended to be smaller and more susceptible to wind damage than those produced from dormant buds. Beck (1977) found similar results for *Liriodendron tulipifera* stump sprouts. He also pointed out that thinning sprouts to the expected number of crop trees was probably unnecessary because of the competition-induced mortality in such circumstances. In repeated harvesting of *Populus tricocarpa* cuttings planted in the Pacific Northwest, DeBell (1975) noted that spacing had a significant effect on yields for the first harvest, but subsequent coppice stands showed little difference in yields across initial plantings and spacings.

Factors found critical by these authors, when included in models for initial sprout frequency, growth and mortality, offer the opportunity for improved screening of superior clones. The specific

1/ Research supported by the College of Forestry and the Agricultural Experiment Station, University of Minnesota, St. Paul; and the USDA Forest Service, North Central Forest Experiment Station, under Cooperative Research Agreement #13-687.

2/ The authors are Professor, Research Assistant, and former Visiting Scientist, Department of Forest Resources, College of Forestry, University of Minnesota, St. Paul. Dr. Dudek was on leave from the faculty of Forestry, Warsaw Agricultural University, Warsaw, Poland, during part of the project.

objectives of this study were to analyze available *Populus* coppice stand growth data from the Rhinelander, Wisconsin, Nursery and: (1) compare clones on the basis of sprouting ability, stand yield, and the relationship of these to parent stand spacings; (2) develop expressions for coppice stand growth and yield components; and (3) develop a computer model integrating this information on coppice stand development with existing information on the development of older stands grown from cuttings.

METHODS

Data

The data for this study were collected from a study of various clones established at the Rhinelander nursery in 1973. Small multispaced plots were established from cuttings and then harvested at age 4 in December 1977. Each clone was represented by only one plot due to logistical considerations at the time. Sample stump locations were subsequently examined in April 1979, October 1979, and November 1980 to establish sprout height, dbh and frequency records. Observations were taken on all sprouts greater than 0.5 m tall and only sprouts within one meter of the parent stump were included. Nearly all sprouts were within 0.5 m of the parent stump. Sprout height and Dbh were observed to the nearest 0.1 m and mm, respectively. The number of stumps examined by spacing and approximate areas per tree were:

Spacing (m)	Stumps Observed	Area per tree (m^2)
.3048	3	.0929
.6096	3	.3716
1.2192	4	1.4864
.3048 x .6096	3	.1858
.3048 x 1.2192	4	.3716
.6096 x 1.2192	4	.7432

An additional one to four parent stand trees left uncoppiced in the northeast corner of the plot were also observed for height and dbh growth. These trees were dominant or codominant stems retained to suggest height-Dbh-age relationships for larger trees as a guide to model development. The parent stand plot and sample stump locations are noted in Figure 1. The clones studied are described in Table 1. Note that clones 5258 and 5266 died during the growing season following harvesting and are not considered further here. Also, 5260 *Populus Tristis* #1, is included in Table 1 for reference, but it was not among the clones coppiced for this study.

These plots were the same ones described by Meldahl (1979) and they continued to receive intensive culture fertilization and irrigation treatments (see Meldahl, 1979) following the 1977 coppicing.

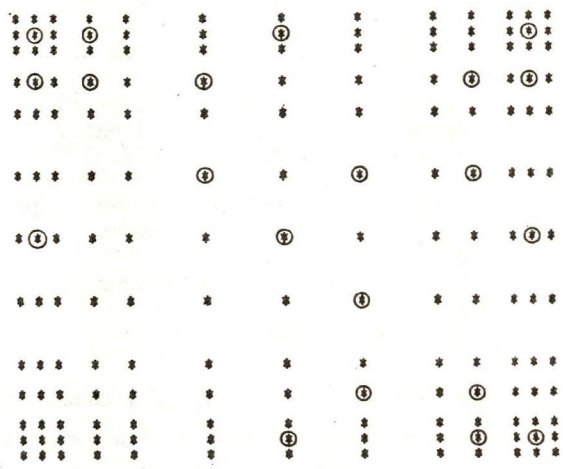


Figure 1.--Multispaced plot design. The narrowest spacing (at each corner) is .3048 m. The widest spacing is 1.2192 m (in the plot center). Parent tree stump locations sampled for sprout data are circled.

Data Analysis and Model Development

Sprout Component

Preliminary analysis of the coppice plot data suggested considerable variability in mortality between clones and years. Average mortality rates across spacings by clone are given in Table 2. The mortality rate of stumps and sprouts was similar and usually the highest for the narrowest spacings, but exceptions to this were frequent. Also, third year mortality (age 2-3) was frequently higher than that for the second year. Results were also confounded by a few small stems growing above the countable height (0.5 m) during the second and third years. Because of this lack of consistency in the pattern of mortality, no simple model fit the data well. Consequently, the mean rates in Table 2 were used for growth model development and projections for all spacings.

As a guide to management, it was noted that the number of sprouts per stump after coppicing was strongly related to the parent stand spacing. Table 3 indicates the number of live sprouts per stump at the end of the growing season following coppicing by clone area per tree.

Table 1.--*Populus* clones studied.

Percentage	Source number	Received from	Supplier's number(s)
Populus spp.	5258	Indian Head, Sask.[1/]	---
Populus tristis Fisch. x *P. balsamifera* L. cv. Tristis #1	5260	Indian Head, Sask.[1/]	---
Populus cv. Candicans x *P.* cv. Berolinensis	5262	Upper Darby, Pa.[2/]	NE-387
Populus cv. Candicans x *P.* cv. Berolinensis	5263	Upper Darby, Pa.[2/]	NE-386
Populus cv. Angulata x *P. tricho-* Torr. & Gray	5266	Upper Darby, Pa.[2/]	NE-372
Populus nigra L. x *P. laurifolia*	5272	Upper Darby, Pa.[2/]	NE-1
Populus x *euramericana* (Dode) Guinier cv. eugenii	5326	Maple. Ontario[3/]	DN-34
Populus cv. Betulifolia x *P. trichocarpa* Torr. & Gray	5331	Upper Darby, Pa.[2/]	NE-299
Populus cv. Betulifolia x *P. trichocarpa* Torr. & Gray	5332	Upper Darby, Pa.[2/]	NE-298
Populus x *euramericana* (Dode)	5377	Ames, Iowa[4/]	---

1/ Wm. Cram, P.F.R.A., Tree Nursery, Canada Dept. of AGric., Indian Head, Saskatchewan.

2/ Northeastern Forest Experiment Station, Upper Darby, PA.

3/ Research Branch, Ontario Div. of Lands and Forests, Maple, Ont.

4/ Forestry Department, Iowa State University, Ames, Iowa.

Table 2. Average sprout mortality rates by clone for coppiced stands.

Clone	Sprout Mortality Rate	
	Age 1-2 years	Age 2-3 years
	- percent -	
5262	71	63
5263	77	54
5272	63	62
5326	50	64
5331	57	67
5332	17	53
5377	44	56

Table 3. Number of live sprouts per stump at age 1 year following coppicing by clone and parent stand area per stump.

Clone	Parent Stand Area per Stump - m^2				
	.0929	.1858	.6096	.7432	1.4864
5262	4.0	10.5	13.7	20.3	29.0
5263	6.3	5.0	11.3	26.0	27.0
5272	18.0	19.0	17.7	27.2	16.7
5326	1.0	6.8	5.1	6.3	11.8
5331	2.7	11.0	12.3	16.5	25.5
5332	0.7	8.0	11.7	6.2	13.5
5377	2.0	4.8	5.6	5.5	8.8

As a guide to management, it was noted that the number of sprouts per stump after coppicing was strongly related to the parent stand spacing. Table 3 indicates the number of live sprouts per stump at the end of the growing season following coppicing by clone and area per tree.

The average height and dbh of sprouts over all clones was only weakly correlated (positively) with area per stump at the end of the first year, but the correlation increased greatly the second and third years. The correlation of the maximum observed height and diameters with area per stump was consistently higher than that for mean values. Average heights, and Dbh of sprouts observed the first three years are shown with stems per hectare and biomass values in Table 4. Biomass values were developed from equations given by Ek (1980) for *Populus Tristis* #1 and adjusted for the average specific gravity of stem and branch components of each clone.[3/]

Note that the per acre values given in the table assume tree growth was representative of the nominal spacing. In fact, the small plot size and especially the close proximity of the narrowest spacings to the plot edge suggest the yields are

3/ Average specific gravity values were drawn from personal communication of a draft manuscript by J. E. Phelps, J. G. Isebrands and D. Jowett.

Table 4.--Three year development of coppiced *Populus* clones under intensive culture at selected spacings.

Clone-age (square spacing (m))	Height (m)	Dbh (cm)	Number of trees (thousand per ha)	Stem and branch wood dry weight (t per ha)
5262 - age 1				
(.3)	1.3	.46	431	5.6
(.6)	1.1	.36	260	2.1
(1.2)	1.3	.42	195	2.0
- age 2				
(.3)	3.1	1.46	72	13.0
(.6)	3.3	1.10	9	.7
(1.2)	2.9	1.50	62	12.9
-age 3				
(.3)	6.3	3.50	36	49.9
(.6)	dead			
(1.2)	5.8	3.29	17	21.1
5263 - age 1				
(.3)	1.4	.34	682	4.2
(.6)	1.3	.45	278	3.4
(1.2)	1.5	.55	182	3.3
- age 2				
(.3)	3.0	1.50	72	12.5
(.6)	4.0	2.10	9	3.5
(1.2)	3.2	1.61	62	14.5
- age 3				
(.3)	3.8	1.90	72	21.8
(.6)	5.6	2.80	9	7.0
(1.2)	5.6	3.46	20	29.2
5272 - age 1				
(.3)	1.3	.42	1,938	20.3
(.6)	1.3	.41	413	4.0
(1.2)	1.5	.45	109	1.3
- age 2				
(.3)	2.8	1.18	466	58.6
(.6)	2.9	1.23	170	22.2
(1.2)	2.6	1.27	740	11.3
- age 3				
(.3)	3.8	2.35	251	181.5
(.6)	4.8	2.56	72	54.3
(1.2)	5.5	2.74	20	17.4
5326 - age 1				
(.3)	1.4	.29	108	.4
(.6)	1.1	.50	81	1.3
(1.2)	1.1	.32	79	.4
- age 2				
(.3)	1.7	.50	36	.4
(.6)	3.3	1.84	36	11.6
(1.2)	2.2	1.25	49	7.0
- age 3				
(.3)	dead			
(.6)	5.5	3.22	27	32.4
(1.2)	5.2	2.93	18	18.2

Table 4.-- continued

Clone-age (square spacing (m))	Height (m)	Dbh (cm)	Number of trees (thousand per ha)	Stem and branch wood dry weight (t per ha)
5331 - age 1				
(.3)	1.6	.47	287	3.7
(.6)	1.6	.54	179	3.5
(1.2)	1.6	.62	172	4.6
- age 2				
(.3)	2.2	.65	73	1.8
(.6)	3.5	1.50	27	5.2
(1.2)	2.7	1.46	103	22.4
- age 3				
(.3)	2.6	.70	36	1.1
(.6)	4.5	2.10	18	8.0
(1.2)	5.7	3.26	30	40.9
5332 - age 1				
(.3)	1.6	.35	72	.4
(.6)	1.6	.60	278	6.2
(1.2)	1.6	.56	91	1.7
- age 2				
(.3)	1.9	.58	72	1.4
(.6)	2.5	1.18	224	26.7
(1.2)	2.5	1.30	86	13.6
- age 3				
(.3)	2.6	.80	36	1.3
(.6)	4.6	2.42	81	49.2
(1.2)	4.4	2.52	35	25.2
5377 - age 1				
(.3)	1.0	.43	215	2.2
(.6)	1.1	.50	108	1.7
(1.2)	1.3	.55	59	1.1
- age 2				
(.3)	dead			
(.6)	4.0	3.40	9	12.4
(1.2)	2.8	1.45	44	8.0
- age 3				
(.3)	dead			
(.6)	6.0	4.20	9	19.1
(1.2)	5.0	3.15	20	22.5

overestimates of what might be attained for large regularly spaced stands (see for example Zavitkovsky, 1981).

The results shown in Table 4 indicates clone 5272 was the most productive at all three ages. Clones 5262, 5331 and 5332 were next best and produced yields similar to each other at all three ages. Unfortunately, the small plot and stump sample sizes and associated variable mortality obscurred the relationship of yields to spacing. Table 5 suggests that parent stand densities of 25,000-50,000 stems per ha were most productive to coppice age 3. Conversely, Table 5 may simply indicate those stumps where survival and growth was high--perhaps due to mortality of nearby stumps. It was thus apparent that meaningful interpretations would require analysis of all of the data. This was done by consideration of models described below.

Table 5. Maximum stem and branch wood yields by clone and spacing for ages 1, 2 and 3 years following coppicing.

Clone	Age 1 - (spacing)	Age 2 - (spacing)	Age 3 - (spacing)
5262	8.7 (.3x.6)	33.5 (.3x1.2)	69.6 (.3x1.2)
5263	8.2 (.3x1.2)	33.4 (.3x1.2)	122.1 (.3x1.2)
5272	20.3 (.3x.3)	58.6 (.3x.3)	181.5 (.3x.3)
5326	2.9 (.3x.6)	11.6 (.6x.6)	32.4 (.6x.6)
5331	12.0 (.3x.6)	40.6 (.3x.6)	94.2 (.3x.6)
5332	7.5 (.3x.6)	41.1 (.3x.6)	92.4 (.3x.6)
5377	4.2 (.3x.6)	19.0 (.3x1.2)	52.2 (.3x1.2)

Given the above data on the coppice plots, the following models were fitted to describe mean sprout height and diameter growth

$$H_s = b_1 (1 - e^{-b_2 A_c})^{b_3} T^{b_4}$$

maximum SE = .76
minimum R^2 = .80

and

$$D_s = b_0 + b_1 H^{b_2} A_c^{b_3} T^{b_4}$$

maximum SE = .23
minimum R^2 = .96

where H_s is mean total height of sprouts (m), A_c is coppice stand age (years), T is stems per hectare in the parent stand, D_s is quadratic mean Dbh of sprouts over 1.37 m tall, and the b_is are constants that differ for each equation. The maximum standard error (SE) and minimum R^2 values across the seven clones from model fitting are also given. Note that although the H_s and D_s observations used for these fits were actually mean values, in later simulation, these models were applied to individual sprouts. Also, the close relationship of sprout height to D_s for the first three years after coppicing precluded the need for an explicit diameter growth equation. The coefficients for these and other models noted below are given by Lenarz and Ek (1983, Appendix 3). Subsequently, these data and equations are refered to as those for sprout growth.

Tree Component

The next step in model development was to synthesize, in equation form, the growth projections to age 20 made for the same *Populus* clones by Meldahl (1979). Meldahl's projections were based upon calibration of the FOREST distance dependent individual tree based stand growth simulation model for trees of cutting origin planted at regular spacings (see Ek and Monserud, 1975, for a general description of the FOREST model). It was felt that the general relationships of growth to density and age in these projections would provide a first approximation of post age three relationships for the development of sprouts from coppiced stands. The projection data used was drawn from Meldahl's tables of 20 year plot interior projections results for each clone for various spacings. Specific tables used were his Appendix 3 Tables 32-39, 45-52, 58-65, 71-78 and for clone 5260, Tables 28, 41, 54 and 67. The following models were then used to describe table values.

$$\Delta H = b_1 (H^{b_2} - b_3 H) A^{b_4} N^{b_5}$$

maximum SE = .17
minimum R^2 = .91

$$\Delta D = b_1 (D^{b_2} - b_3 D) A^{b_4} N^{b_5}$$

maximum SE = .26
minimum R^2 = .95

$$\frac{\Delta N}{N} = b_1 (H^{b_2} + b_3 N^{b_4})$$

maximum SE = .02
minimum R^2 = .88

where ΔH is mean height growth (m), A is stand age, N is current stems per hectare, and the b_is are constants that differ for each equation. Unfortunately, Meldahl's tables included only clones 5258, 5260, 5262, 5263, 5266, 5326, 5331, 5332 and 5377. Such tree growth data was not available for clone 5272. Conversely, no sprout data was available for clones 5258, 5260, and 5266. Study of growth patterns and suggestions by J. Zavitkovski[4/] then led to the assumption of tree growth model

[4/] Personal communication, August 30, 1982.

fits from clone 5377 as a first approximation of the growth of 5272.

Subsequently, the data and equations are referred to as those for tree growth. The tree model coefficients are given by Lenarz and Ek (1983, Appendix 3).

The above equations were then assembled in the form of a small distance independent individual tree based stand growth model called POPGROW (see Lenarz and Ek (1983) for details of this model; Ek and Dudek (1980) describe this type of model in detail). This program reflects coppicing practice and short rotation intensive culture in that it allows input of a list of stems (sprouts), each associated with a particular stump. The sprouts are then grown (projected) to age three by the above equations for coppice stems. Subsequently, their growth is projected by the tree growth equations derived from Meldahl (1979). Growth and yields are described by annual output of mean projected height, Dbh, numbers of trees, basal area, biomass by tree component, total biomass and stem wood volume. The biomass equations used were those by Ek (1980) with adjustments noted earlier for differing specific gravities between clone. The stem volume output is based on a fit of Table 3 from Gevorkiantz and Olsen (1955).

The first projections with POPGROW identified a problem noted by Isebrands *et al.* (1982) and Zavitkovsky (1981, 1982). Comparisons of Meldahl's projections with observed plot values at ages 5, 9 and 10 indicated overestimation of height by approximately 4-6 percent. Diameter estimates from Meldahl were close to an actual value at age 5 but overstimated an actual value by up to 91 percent at age 10. Conversely, Meldahl's model underestimated survival by 4 to 7 percent at ages 5 and 10, respectively. These results were incorporated in POPGROW by reducing predicted sprout and tree height growth by 6 percent and reducing tree Dbh growth (post age 3) by 58 percent. Other adjustments incorporated after trial runs included constraining tree growth at wide spacings and at high basal areas. The first was accomplished by constraining the trees per hectare term in the tree height and Dbh growth to no less than 4445 (corresponding to a spacing of 1.5 m). This was necessary since there was no growth data for spacings beyond 1.2 m and because wider spacings were expected to have near maximum diameter growth that would not increase with further spacing. The other adjustments altered tree Dbh growth for stands with greater than 50 m^2 of basal area by the expression $1 - B/200$ and mortality rates by $1/[1 - B/200]$ where B = basal area - 50. In effect, 250 m^2 was considered a maximum possible stand density for SRIC. Further adjustments including constraining height and Dbh growth to maximum values expected for open grown trees were redundant, i.e., they had little or no effect after the adjustments noted above.

The adjustments to prediction models for Meldahl's growth data were considered appropriate because his original model fit allowed excessive and almost linear extrapolation of early diameter growth. Although the adjustments produced a more realistic pattern of growth, they should still be considered quite speculative, especially beyond age ten years. In particular, the lack of data on the long term diameter growth-density relationship made the adjustment process very subjective.

Analysis of Projections

Projections for the seven coppiced clones to age 15 are given in Table 6. Note that these projections are from observed initial conditions at age one and that they utilize average rather than spacing specific mortality for each clone. Also, they incorporate the model adjustments described in the previous section. Complete tables of projections for each clone and spacing are given in a supplement to this paper.[5/]

Table 6 indicates maximum mean annual increment values for stems and branch wood from 4.6 to 15.6 tons per hectare per year (6.4 - 15.6 excluding clone 5377). It is further significant that such yield projections were obtained for a variety of clones and spacings and that the mean annual increment curves appear to stay near their maximum for several years. It appears that these yields could be obtained early at narrow spacings, but that wider spacings would eventually catch up and usually surpass the narrow. For interpretation, it should be emphasized that there is much variability between spacings in the original data and in the projections. For example, projected yield values for clone 5272 at age 3 are possible, but unlikely for large plots.

These projections should be considered another step in the refinement of earlier reports on SRIC yields by Ek and Dawson (1976) and Meldahl (1979). Present values agree roughly with maximum temperate zone short rotation yields suggested by Cannell and Smith (1980). For clarification, however, it should be understood that the present study projects yields for SRIC populus coppice stands under carefully (but not perfectly) controlled experimental conditions. That is also what was intended by Ek and Dawson (1976) and Meldahl (1979). For large scale operations yields per unit area would likely

---

5/ Ek, A. R., J. E. Lenarz and A. Dudek. 1983. Supplemental Growth and Yield Tables for "Growth and Yield of *Populus* Coppice Stands Grown Under Intensive Culture." University of Minnesota, College of Forestry. Mimeo. 29 p. Available upon request.

be at least 15-20 percent lower. That shortfall would be due to variability in environmental factors and greater difficulty in applying cultural practices uniformly. Without intensive culture, the yields would be substantially lower.

Table 6. Fifteen year projections of coppice stand development and mean annual stem and branch wood yield for selected *Populus* clones and parent stand spacings.

	Parent Stand Spacing (m)[1/]												
	.3 x .3				1.2 x 1.2				2.4 x 2.4				MAI
Age	H	Dbh	N	MAI	H	Dbh	N	MAI	H	Dbh	N	MAI	Range
Clone 5262													
3	4.4	2.2	47	7.5	4.4	2.2	22	3.1	4.4	2.2	5	0.8	
5	6.2	3.0	34	6.8	6.6	3.2	18	4.2	7.3	3.9	5	1.9	
10	10.2	5.2	19	7.2	11.3	5.9	13	6.6	14.0	8.8	5	6.0	
15	13.4	7.5	13	8.2	14.9	8.8	10	8.8	18.2	13.6	4	10.5	8.2-10.5
Clone 5263													
3	4.3	2.1	74	10.2	5.1	2.9	20	5.7	5.5	3.2	5	1.9	
5	6.0	2.9	46	7.9	7.6	4.2	17	7.5	8.4	5.6	5	4.2	
10	9.7	4.8	23	7.1	12.5	7.6	12	11.0	15.1	11.6	4	10.7	
15	12.9	7.0	15	7.5	16.0	10.6	9	12.5	19.0	16.8	4	15.6	7.5-15.6
Clone 5272													
3	4.0	1.8	272	39.5[2/]	4.9	2.3	15	2.7	5.4	2.6	4	0.9	
5	5.0	2.3	80	8.8	7.2	3.4	14	3.7	8.4	4.1	4	1.6	
10	8.1	4.1	33	7.3	12.4	6.3	11	6.5	14.6	8.1	3	3.8	
15	11.0	6.2	20	8.0	15.6	9.4	8	9.3	18.3	12.2	3	6.4	6.4-9.3
Clone 5326													
3	3.9	2.0	19	2.3	4.1	2.2	14	2.1	4.4	2.4	4	0.7	
5	5.9	2.8	17	3.0	5.4	3.2	13	3.0	7.4	4.0	3	1.4	
10	10.2	5.1	13	4.8	11.1	5.8	10	5.2	13.7	8.6	3	4.1	
15	13.5	7.6	10	6.7	14.6	8.6	8	7.5	17.6	13.2	3	7.3	6.7-7.5
Clone 5331													
3	4.4	2.0	41	5.6	5.0	2.5	25	5.8	5.3	2.8	6	1.8	
5	6.2	2.9	31	5.8	7.2	3.6	20	7.0	8.3	4.7	6	3.7	
10	10.1	5.2	18	7.6	11.6	6.6	14	10.3	14.4	9.8	5	9.5	
15	13.3	7.9	13	9.6	14.9	9.7	10	12.8	18.3	14.7	4	15.1	9.6-15.1
Clone 5332													
3	4.2	1.9	28	2.8	4.5	2.1	35	4.7	4.7	2.2	9	1.3	
5	6.3	2.9	23	3.9	6.6	3.1	27	5.5	7.6	3.8	8	2.7	
10	11.0	5.6	15	6.7	11.1	5.7	17	8.0	13.7	8.2	7	7.5	
15	14.7	8.6	11	9.5	14.6	8.6	12	10.3	17.7	12.7	6	12.4	9.5-12.4
Clone 5377													
3	4.0	2.0	53	6.4	4.3	2.2	15	2.2	4.3	2.2	4	0.6	
5	5.6	2.7	39	6.1	6.6	3.3	13	3.1	7.3	3.6	4	1.0	
10	9.2	4.8	23	6.8	11.4	6.1	10	5.4	13.5	7.3	3	2.6	
15	12.3	7.0	16	8.1	15.0	9.1	8	7.8	17.5	11.2	3	4.6	4.6-8.1

[1/] Definition of terms:

H = mean total height (m)
Dbh = mean Dbh (cm)
N = stems per ha (thousands)
MAI = mean annual stem and branch wood increment (metric tons per hectare per year)

[2/] An extreme example of data and projection variability.

LITERATURE CITED

Beck, D. E. 1977. Growth and development of thinned versus unthinned yellow-poplar sprout clumps. USDA For. Ser. Res. Pap. SE-173. 11 p.

Cannell, M. G. R. and R. I. Smith. 1980. Yields of minirotation closely spaced hardwoods in temperate regions: Review and appraisal. Forest Science 26:415-428.

DeBell, D. S. and L. Alford. 1972. Sprouting characteristics and cutting practices evaluated for cottonwood. Tree Planters Notes 3(23):1-3.

DeBell, D. S. 1975. Short-rotation culture of hardwoods in the Pacific Northwest. Iowa State Jour. Res. 49:345-352.

Ek, A. R. 1980. Mensurational and biomass relations for *Populus 'tristis* #1' under intensive culture. USDA For. Ser. Res. Note NC-260. 4 p.

Ek, A. R. and A. Dudek. 1980. Development of individual tree based stand growth simulators: Progress and applications. University of Minnesota Department of Forest Resources Staff Paper Series No. 20. 25 p.

Ek, A. R. and D. H. Dawson. 1976. Actual and projected growth and yields of *Populus 'tristis* #1' under intensive cultures. Can. J. For. Res. 6:132-144.

Ek, A. R. and J. D. Brodie. 1975. A preliminary analysis of short-rotation aspen management. Can. J. For. Res. 5:245-258.

Ek, A. R. and R. A. Monserud. 1974. FOREST: A computer model for simulating the growth and reproduction of mixed species forest stands. Univ. of Wisc. Coll. Agric. and Life Sciences Res. Rep. R-2635. 13 p. plus appendices.

Gevorkiantz, S. R. and L. P. Olsen. 1955. Composite volume tables for timber and their application in the Lake States. USDA Technical Bulletin 1104. 51 p.

Isebrands, J. G., A. R. Ek and R. S. Meldahl. 1982. Comparison of growth model and harvest yields of short rotation intensively cultured *Populus*: A case study. Can. J. For. Res. 12:58-63.

Lenarz, J. E. and A. R. Ek. 1983. POPGROW: A model for *Populus* coppice stand development. University of Minnesota Department of Forest Resources Staff Paper Series No. 34. 29 p.

Meldahl, R. S. 1979. Yield projection methodology and analysis of hybrid *Populus* based on multispaced plots. Ph.D. Thesis, Univ. Wisconsin, Madison (Univ. Microfilms No. 80-07560). 238 p.

Zavitkovsky, J. 1982. Projected and actual biomass production of 2- to 10-year old intensively cultured *Populus 'tristis* #1'. Paper presented at Short Rotation Intensive Culture Research Program Review. Rhinelander, Wis. January 26-27, 1982.

Zavitkovsky, J. 1981. Small plots with unplanted border can distort biomass production studies. Can. Jour. For. Res. 11:9-12.

PROJECTED AND ACTUAL BIOMASS PRODUCTION OF 2- TO 10-YEAR-OLD INTENSIVELY CULTURED POPULUS 'TRISTIS # 1'

by

J. Zavitkovski[1]

Abstract.--Intensively cultured plantations of Populus 'Tristis # 1' produce more than 10 mt/ha/year of woody biomass at most spacings as long as they are harvested when mean annual biomass increment (MABI) culminates. In addition, fully stocked plantations produce up to 4.4 mt/ha of leaf litter. Plantations of other poplar clones produce about 30% more woody biomass, but leaf litter production is about the same as in P. 'Tristis # 1'. Because projected biomass productions of P. 'Tristis # 1' were 42 to 182% higher than the actual productions, caution must be exercised when using projected production values. The discrepancy increased with age. P. 'Tristis # 1', although less productive than several other poplar clones in our tests, showed no major deficiencies in 12 years of experimentation. Various P. x euramericana clones have suffered sun scalding in northern Wisconsin, and other clones, including the highly productive NE-299 (NC-5331), have suffered wind damage. P. 'Tristis # 1' should be officially recommended for planting in the Lake States.

Populus 'Tristis # 1', a hybrid between P. tristis Fisch. and P. balsamifera L.,[2] was among the first hybrid poplars included in the short-rotation intensive culture (SRIC) studies at the Forestry Sciences Laboratory (FSL) in Rhinelander, Wisconsin (USDA Forest Service 1976). Plantings were established in the FSL nursery in 1970 and again in 1973 at spacings ranging from 0.23 x 0.23 to 2.4 x 2.4 m (9 x 9 in to 8 x 8 ft). In 1974, an additional planting was established at 3.6 x 3.6 m (12 x 12 ft). In 1976/77, large plantings (0.25 ha or 0.6 acre) of Tristis and three other clones were established on the Harshaw Forestry Research Farm near Rhinelander (Hansen et al. 1979). Many poplar hybrids have been introduced and tested since 1970, but Tristis is still considered among the most promising clones for this part of the Lake States.

Growth and production data for the 1970 plantings were summarized and published by Dawson and co-workers (Crist and Dawson 1975, Dawson et al. 1976, Ek and Dawson 1976a, b, and Zavitkovski et al. 1976). Results of the 1973 studies were published by Meldahl (1979). Studies on the utilization potential of 5-year-old Tristis were published by Isebrands et al. (1979).

Serious problems often arise when biomass production estimates are based on small plots with unplanted borders (Zavitkovski 1981a). For example, the biomass production of over 20 mt/ha/year predicted by Ek and Dawson (1976a, b) for Tristis may have been far too optimistic. The objectives of this report are to:

(1) summarize the actual growth and biomass production of all available Tristis plantings at Rhinelander during the first rotation phase[3], and

(2) compare the actual growth and aboveground biomass production with the predicted values of Ek and Dawson (1976a, b) and Meldahl (1979).

[1]Research Forester, North Central Forest Experiment Station, Forestry Sciences Laboratory, Rhinelander, WI 54501

[2]Hereafter Tristis

[3]First rotation phase refers to plantations established from cuttings.

METHODS

In each plantation, height and DBH were measured annually in the fall or winter. In the 1973 FSL nursery plantings, a "harvest area," consisting of about one-sixth of the total area, was designated for destructive sampling. In the large plantings on the Harshaw Forestry Research Farm, 16 permanent plots were randomly selected in each planting and DBH's in each plot were measured annually. Destructive sampling for biomass estimation was conducted in other parts of the plantings. After all non-destructive measurements were taken, the trees were divided into five or six DBH classes; one tree was randomly selected and harvested from each DBH class. Trees were cut at ground level and height was measured on the ground with a tape; trees were then separated into components and taken to the laboratory for further processing.

In the laboratory, bark was stripped from a subsample of stems and branches and all materials were dried at 70°C to constant weight. Dry weights were used to develop regression equations suitable for estimating the biomass of all trees in a plot. The biomass of all Tristis plantings was estimated by means of Ek's (1980) equations based on both the DBH and height. Biomasses of other poplar hybrid plantings from age 2 to 6 were estimated by means of allometric equations, based on DBH alone, which were developed separately for each clone and spacing. Biomass of each planting was expressed per unit land area (hectare or acre).

Biomass production of Tristis plantings, expressed as mean annual biomass increment (MABI) in mt/ha/year, is presented separately for the woody parts (stems and branches with bark) and foliage. For comparison, MABI's of several other poplar hybrids planted at the Harshaw Forestry Research Farm in 1976/77 are also presented.

RESULTS AND DISCUSSION

Woody Biomass

For the first few years, the Tristis plantations with close spacing were more productive than those with wider spacing, but with the increasing age, the MABI's of the more open plantings caught up and reached about the same production (Table 1). For example, at age 5 the MABI's of the 0.3 x 0.3 and 0.6 x 0.6 m (1 x 1 and 2 x 2 ft) plantings were 9.9 and 8.9 mt/ha/year, respectively. By comparison, the MABI of the 2.4 x 2.4 m planting was only 3.7 mt/ha/year at age 5, but at age 10 it had reached 10.4 mt/ha/year. We don't know what MABI's would have developed in the two denser plantings by age 10. They were removed at age 6 when they were found unsuitable for further biomass studies mainly because of a pronounced edge effect (Zavitkovski 1981a).

Shape of the growth curves suggests that woody biomasses of the 2.4 x 2.4 and 3.6 and 3.6 m plantings will continue increasing beyond their present levels. Their MABI's may culminate between 12 and 20 years.

Table 1.--Aboveground woody biomass production of 2- to 10-year-old Populus 'Tristis #1' at various spacings[1]

AGE	(IN MEAN ANNUAL BIOMASS INCREMENT - MABI)						
	SPACING (m)						
Yrs.	0.3x0.3	0.6x0.6	1.1x1.1[2]	1.2x1.2	2.0x2.0[2]	2.4x2.4	3.6x3.6
	mt/ha/year						
2	3.7	1.9	1.6	1.1	0.2	0.2	0.1
3	7.0	4.9	3.3	2.3	.9	.6	.3
4	9.0	7.9	6.0	5.1	3.8	2.3	1.0
5	9.9	8.9	6.5	6.8	5.5	3.7	1.7
6	-	-	9.6	-	9.1	4.8	3.2
7	-	-		-		6.5	4.8
8	-	-		-		8.4	5.6
9	-	-		-		9.7	6.2
10	-	-		-		10.4	

[1]Data for the 2- to 5-year-old stands at the Forestry Sciences Laboratory Nursery were adapted from Meldahl (1979). Data for the remaining stands were based on our measurements. Biomass of Populus 'Tristis # 1' was calculated according to Ek (1980).

[2]Plantings at the Harshaw Forestry Research Farm. All data based on our measurements.

It appears that similar MABI's may be reached in SRIC poplar plantations that were established at various spacings as long as they are harvested when their MABI culminates. Similar principles have been proposed for volume production by Moller (1945), Assmann (1953), and Ek and Brodie (1975), and for biomass production by Hutnik and Hickok (1967).

It is important to note that although they may be similar in terms of sustained annual production, the dense and open poplar plantations will feature very different stand structures -- i.e., many slender sapling-like trees/ha in dense plantations and a few large trees/ha in the open plantations. The manager (or economist) can select the best system.

One biological factor to consider when deciding stand density and rotation length will be the average tree size in the final harvest and its ability to coppice. It is possible that coppicing of large trees will be inhibited, preventing successful regeneration. Our present knowledge on coppicing of hybrid poplars in relation to age and size of the tree is inadequate.

At the Harshaw Forestry Research Farm, the age-6 MABI of clone NE-299 (NC-5331) was about 30% higher than that of Tristis, which was in turn substantially higher than the MABI's of two P. x euramericana clones (DN-34 or NC-5326, and NC-5377 cv. Wisconsin # 5) (Table 2). Moreover, the Tristis plantings were healthiest, had better form, and were less susceptible to wind and sun damage than the other clones.

Leaf Litter Biomass and LAI

Compared with natural stands of various broadleaved species of the temperate zone, the intensively cultured Tristis plantations produce substantially more leaf litter and LAI.

Leaf litter production, like the MABI's of woody parts, was strongly affected by stand density during the early years of plantation development (Table 3). Leaf litter quantities of over 4 mt/ha were collected in dense plantings during the first 5 years and similar quantities several years later in the open plantings. The data suggest that 4.4 mt/ha may be the upper limit of leaf litter production in Tristis regardless of spacing (Zavitkovski 1981b). This level was reached in the 2.4 x 2.4 m planting at age 8 (Table 3). In general, leaf litter production showed little annual variation, a finding consistent with the MABI data discussed in the preceding section (Table 1).

Cumulative leaf area index, LAI, essentially followed the same trend as leaf litter production (Table 3). The highest cumulative LAI's were reached at age 6 in plantings spaced from 0.3 x 0.3 to 1.2 x 1.2 m (1 x 1 to 4 x 4 ft), and 1 year later in the 2.4 x 2.4 m (8 x 8 ft) planting. The uniformity of LAI's over a period of 6 years, except for minor unexplained variations (e.g., LAI 5.7 at age 9), is consistent with that found in the leaf litter production.

Leaf litter production and LAI's from 2- to 6-year-old hybrid poplar plantings on the Harshaw Forestry Research Farm were similar to those reported for Tristis (Table 4). In only one instance, the 0.7 x 0.7 m NE-299 (NC-5331) planting at age 4, did leaf litter production (5.2 mt/ha) exceed the highest (4.4 mt/ha) level for Tristis (Table 3). In general, the LAI's were also similar to those of Tristis.

Comparison of Actual and Predicted MABI's

The MABI's projected by Ek and Dawson (1976 a, b) and Meldahl (1979) for Tristis were considerably higher than the actual measured values. This pattern was also documented for the 1.2 x 1.2 m (4 x 4 ft) 5-year-old Tristis planting that had to be harvested because of wind damage (Isebrands et al. 1982). In that study, the aboveground biomass of the planting, excluding leaves, was 37.92 mt/ha, and the woody MABI was 7.6 mt/ha/year (Isebrands et al. 1979). The projected woody biomass and woody MABI were 53.8 mt/ha and 10.8 mt/ha/year, respectively (Ek and Dawson, 1976a, b), or about 42% higher than the actual.

Table 2.--Aboveground woody biomass production of 2- to 6-year-old hybrid poplars at various spacings at the Harshaw Forestry Research Farm (In mean annual biomass increment - MABI)

AGE	SPACING (m) AND CLONE							
	0.7x0.7	1.1 x 1.1			2.0 x 2.0			
	NE-299 NC-5331	NE-299 NC-5331	NC-5260	NC-5377	NE-299 NC-5331	NC-5260	NC-5377	DN-34 NC-5326
	mt/ha/year							
2	2.2	1.4	1.6	0.7	0.7	0.2	0.2	0.2
3	5.8	4.5	3.3	2.5	2.7	.9	.6	.5
4	8.2	7.0	6.0	4.0	5.7	3.8	1.6	1.3
5	8.7	-	6.5	4.5	7.3	5.5	3.7	1.7
6	12.3	-	9.6	8.4	12.1	9.1	6.2	4.6

Table 3.--Leaf litter biomass and leaf area index (LAI) of 3- to 10-year-old Populus 'Tristis #1' at various spacings[1]

AGE	SPACING (m)					
	0.3x0.3	0.6x0.6	1.1x1.1[2]	1.2x1.2[3]	2.0x2.0[2]	2.4x2.4
			LEAF LITTER DRY WEIGHT (mt/ha)			
3	3.3	3.2	2.3	2.6	0.7	1.6
4	4.0	4.1	4.1	3.2	1.8	2.5
5	3.4	3.4	3.5	-	3.0	2.5
6	4.2	4.2	3.7	-	3.6	3.4
7	-	-	-	-	-	3.9
8	-	-	-	-	-	4.4
9	-	-	-	-	-	3.6
10	-	-	-	-	-	4.0
			LEAF AREA INDEX (LAI)			
3	6.0	5.6	3.8	4.9	0.6	1.6
4	6.9	7.1	7.3	5.9	1.6	3.2
5	-	7.3	6.1	-	5.7	-
6	8.6	8.7	7.8	-	8.2	6.8
7	-	-	-	-	-	8.4
8	-	-	-	-	-	7.5
9	-	-	-	-	-	5.7
10	-	-	-	-	-	8.3

[1]Data for 3- to 7-year-old stands, except for stands at the Harshaw Forestry Research Farm, are from Zavitkovski (1981b).

[2]Stands at the Harshaw Forestry Research Farm were established in 1976/77. All other stands were established in 1973 at the Forestry Sciences Laboratory Nursery.

[3]Stand was damaged by wind and harvested in 1977.

Table 4.--Leaf litter biomass and leaf area index (LAI) of 3- to 6-year-old hybrid poplar plantations at various spacings[1]

AGE	SPACING (m) AND CLONE							
	0.7x0.7	1.1x1.1			2.0x2.0			
	NE-299 NC-5331	NE-299 NC-5331	NC-5260	NC-5377	NE-299 NC-5331	NC-5260	NC-5377	DN-34 NC-5326
				LEAF LITTER DRY WEIGHT (mt/ha)				
3	3.0	2.4	2.3	1.5	1.7	0.7	0.6	0.4
4	5.2	4.4	4.1	3.2	4.4	1.8	1.4	1.4
5	4.4	lost[2]	3.5	2.6	2.6	3.0	2.0	1.8
6	4.3	-	3.7	3.1	3.9	3.6	2.7	2.9
				LEAF AREA INDEX (LAI)				
3	5.7	6.2	3.8	1.5	3.5	0.7	0.8	0.7
4	7.3	8.5	7.4	2.6	6.6	1.7	1.4	2.0
5	6.9	lost[2]	6.2	3.4	4.4	5.7	2.6	2.1
6	7.0	-	7.8	5.1	6.1	8.2	3.9	4.1

[1]Plantations at the Harshaw Forestry Research Farm

[2]Stand was damaged by windstorm and harvested.

The actual MABI of the 10-year-old, 2.4 x 2.4m Tristis planting was 10.4 mt/ha/year (Table 1). Ek and Dawson's (1976a, b) projection was 96% higher (20.4 mt/ha/year) and Meldahl's (1979) projection, based in part on data from the 1973 plantations, was 81% higher (18.8 mt/ha/year) (Table 5). The actual MABI of the 9-year-old, 3.6 x 3.6 m Tristis planting was 6.2 mt/ha/year, whereas Ek and Dawson's projection for a slightly more widely spaced planting (3.9 x 3.9 m) was 182% higher (17.5 mt/ha/year).

Table 5.--Comparison of predicted and actual survival, growth, and biomass production of 9- and 10-year-old Populus 'Tristis #1'

DATA	SURVIVAL		DIAMETER		HEIGHT		MABI[1]	SOURCE
	Trees/ha	%	cm	in	m	ft	mt/ha/year	
			10-YEAR-OLD, 2.4 x 2.4 m (8 x 8 ft) PLANTING					
Actual	1,626	97	9.8[2]	3.9	13.5	44	10.4	Present study
Predicted	1,556	93	26.7[2]	10.5	16.2	53	20.4	Ek and Dawson (1976a,b)
Predicted	1,510	90	18.7	7.4	13.7	45	18.8	Meldahl (1979)
			9-YEAR OLD, 3.6 x 3.6 m (12 x 12 ft) PLANTING					
Actual	716	96	10.1[2]	4.0	12.0	39	6.2	Present study
Predicted	625	93	35.8[2]	14.1	15.5	51	17.5	Ek and Dawson (1976a,b)[3]

[1]Mean annual biomass increment, MABI.

[2]Diameter at 2.5 cm (1 in) above-ground.

[3]Projected for a 3.9 x 3.9 m (12.7 x 12.7 ft) planting.

In summary, models used for estimating biomass production of intensively cultured poplar plantations have consistently overestimated actual growth. Although numerous factors may have contributed to these overestimates (see Isebrands et al. 1982), the results of this study suggest that biomass projections based upon limited data from small plots should be used with caution.

ACKNOWLEDGMENTS

Messrs. Daniel A. Netzer and Terry F. Strong helped with various phases of the study. The study was supported in part by the Department of Energy under an Interagency Agreement DE-AI-05-800R20763.

LITERATURE CITED

Assmann, E. 1953. Bestockungsdichte und Holzerzeugung. Forestwissenschaftliches Centralblatt 72: 69-101.

Crist, John B., and David H. Dawson. 1975. Anatomy and dry weight yield of two Populus clones grown under intensive culture. USDA Forest Serv. Res, Pap. NC-113, 6 p.

Dawson, David H., Jud G. Isebrands, and John C. Gordon. 1976. Growth, dry weight yields, and specific gravity of 3-year-old Populus grown under intensive culture. USDA For. Serv. Res. Pap. NC-122, 7 p.

Ek, Alan R. 1980. Mensurational and biomass relations for Populus 'Tristis #1' under intensive culture. USDA For. Serv. Res.Note NC-260.

Ek, Alan R., and J. D. Brodie. 1975. A preliminary analysis of short-rotation aspen management. Can. J. For. Res. 5: 245-258.

Ek, Alan R., and David H. Dawson. 1976a. Actual and projected growth and yields of Populus 'Tristis # 1' under intensive culture. Can. J. For. Res. 6: 132-144.

Ek, Alan R., and David H. Dawson. 1976b. Yields of intensively grown Populus: Actual and projected. In: Intensive Plantation Culture, USDA For. Serv. Gen. Tech. Rep., North Central For. Exp. Stn. Gen. Tech. Rep. NC-21, p. 5-9.

Hansen, Edward A., H.A. McNeel, Daniel A. Netzer, Howard M. Phipps, Pamela S. Roberts, Terry F. Strong, David N. Tolsted, and J. Zavitkovski. 1979. Short-rotation intensive culture practices for northern Wisconsin. In: Ann. Mtg., North Am. Poplar Council, Thompsonville, MI, p. 47-63.

Hutnik, R.J., and K.H. Hickok. 1967. Effect of spacing on dry matter production in red pine plantations. IUFRO Cong., Sect. 23, p. 314-328. Munich, W. Germany.

Isebrands, J.G., A.R. Ek, and R.S. Meldahl. 1982. Comparison of growth model and harvest yields of short rotation intensively cultured Populus: a case study. Can. J. For. Res. 12(1): 58-63.

Isebrands, Jud G., John A. Sturos, and John B. Crist. 1979. Integrated utilization of biomass - A case study of short-rotation intensively cultured Populus raw material. Tappi 62 (7): 67-70.

Meldahl, Ralph Stuart. 1979. Yield pojection methodology and analysis of hybrid poplars based on multispaced plots. Ph.D. Thesis, University of Wisconsin, Madison, WI, 228 p.

Moller, C.M. 1945. Untersuchungen ueber Laubmenge, Stoffverlust and Stoffproduktion des Waldes. Forst. Forsogsv. Danmark 17: 1-287.

USDA For. Serv. 1976. Intensive plantation culture. Five years research. Gen. Tech. Rep. NC-21, 117 p.

Zavitkovski, J. 1981a. Small plots with unplanted plot border can distort data in biomass production studies. Can. J. For Res. 11(1): 9-12.

Zavitkovski, J. 1981b. Structure and seasonal distribution of litterfall in young plantations of Populus 'Tristis # 1'. Plant and Soil 60: 409-422.

Zavitkovski, J., Jud G. Isebrands, and David H. Dawson. 1976. Productivity and utilization potential of short-rotation Populus in the Lake States. In: Proceedings, Symposium on Eastern Cottonwood and Related Species, B.A. Thielges and S.B. Land, (Eds.), Louisiana State Univ., Baton Rouge, LA, p. 392-401.

YIELD PHYSIOLOGY OF SHORT ROTATION INTENSIVELY CULTURED POPLARS

J. G. Isebrands
N. D. Nelson
D. I. Dickmann
D. A. Michael[1/]

Abstract.--An integrated research approach is described for studying yield physiology of short rotation intensively cultured (SRIC) poplar plantations. Branch architecture differs with clone and stand density, but the clonal ranking of important branch characteristics does not change with spacing. Crown morphological variables have a distinct effect on physiological properties of leaves within the crown. Such variables as leaf age, position, shoot type, and distance to the main stem are all important. Leaf area is linearly related to biomass production in the first 5 years of SRIC plantations. Photosynthetic rate (PgA) is strongly influenced by differences in leaf orientation in the crown. Diurnal patterns of PgA also differ with position in the crown and light climate. PgA is high in clones that exhibit significant autumal green leaf retention. Clones differ distinctly in photosynthate distribution patterns. Both timing of budset and leaf fall are important factors determining these patterns. Current terminal leaves provide most of the photosynthate used for height growth; mature leaves on the upper branches contribute primarily to stem diameter and root growth. Clones with high late-season PgA's also show substantial production of photosynthate, which is exported to the stem and roots. Growth analysis conducted in conjunction with photosynthesis and photosynthate distribution studies led to a better understanding of growth patterns. Stem dry matter production paralleled leaf production during the course of the season. Clones differ in root/shoot ratio during the establishment year so both above- and below-ground growth data are needed to evaluate clonal performance in that year. Silvicultural and genetic implications of the data are discussed and recommendations are given for practical applications of the results. The current understanding of a superior "ideotype" for a SRIC poplar tree is also given.

Basic physiological and genetic investigations of yield have allowed agronomists and horticulturists to improve the productivity of several important crops (Coyne 1980; Evans 1980; Boyer 1982). Fundamental research information has been used to identify which physiological characteristics (or criteria) of the crop are important in determining the efficiency of energy conversion to harvestable yield. Those criteria with high heritability are then used by the plant breeder to choose parents for a breeding program.

1/ Wood Scientist and Plant Physiologist, Forestry Sciences Laboratory, P. O. Box 898, Rhinelander, WI 54501; and Professor and Research Assistant, Department of Forestry, Michigan State University, East Lansing, MI 48824.

Physiological data have also been successfully used to identify the critical stages of plant development; then plant varieties can either be identified or developed that perform well at those critical stages (Freeman 1975). Unfortunately, the complex physiological characteristics correlated with crop yield are often interrelated (Nasyrov 1978) and controlled by multigene systems (Wallace et al. 1976). As a result of this complexity the most successful programs for improving crop yield have been those that utilized the cooperative talents of plant breeders, crop physiologists, and plant biochemists.

The most common approaches to increasing productivity in crops are: 1) optimizing canopy structure, 2) improving photosynthetic rates, and 3) partitioning a large proportion of the total assimilates into yield (harvest index) (Nasyrov 1978). These approaches can also be applied toward increasing productivity of trees because many of the theoretical and conceptual principles of yield are fundamentally similar between cultivated crops and trees (Larson 1969; Ledig 1975; Borlaug 1977).

In 1978 we began a research program designed to provide physiological criteria for improving short rotation intensively cultured (SRIC) poplars. Our goal was to obtain baseline morphological and physiological information on poplar trees grown in the field. An integrated research approach was selected to obtain the baseline information on similar trees. Integrated studies of crown morphology, photosynthesis, and photosynthate distribution were conducted in relation to biomass yield as expressed by traditional growth analysis (see Evans 1972). Studies in each scientific discipline were coordinated so that resultant information would be compatible. Research was conducted each year for 4 years on several clones, beginning with the establishment year. Our philosophy was that detailed physiological data on a few representative clones would be more valuable at the early stages of the research program than scattered data on many clones. We believe that such baseline information can also eventually be applied (within limits) toward the understanding of the physiology of some other promising clones. Studies of the few selected clones were also designed to extend baseline physiological data developed on trees grown in controlled environments and in the greenhouse to trees grown in the field. Information from the field experiments was used to plan further laboratory studies. We hoped that an understanding of baseline physiological mechanisms in field-grown poplars would help explain results of various field tests of establishment and growth. We also hoped that a biological explanation of yield would give forest managers more confidence in selecting clones and choosing cultural practices (Ledig 1975).

The objectives of this paper are to summarize and explain the results to date of our integrated research and to discuss the silvicultural and genetic implications of these results. These morphological and physiological data will also be used to describe what the "ideal" poplar clone (i.e., ideotype; Donald 1968) might be for certain SRIC systems.

The following clonal materials were studied: 1) Populus tristis x P. balsamifera cv. 'Tristis #1' (NC-5260) and P. x euramericana cv. 'Eugenei' (NC-5326)[2/] trees grown in pots for one growing season in both controlled environments and the field (Nelson and Ehlers 1981; 1982); 2) the same two clones grown under SRIC at 0.6 m specing for 4 years; 3) Tristis grown at 1.2 m and 0.6 m spacings for 5 and 6 years (Isebrands and Nelson 1982); 4) P. nigra cv. betulifolia x P. trichocarpa (NE-298) and NC-9922, (probably P. deltoides x P. trichocarpa) grown for 4 years at 1.2 m spacing under a gradient of cultural practices; and 5) P. nigra x P. laurifolia cv. 'Strathglass' (NE-1) grown under SRIC at several spacings for 2 years (Nelson et al.1980 b,c). Details of the establishment and culture of the SRIC poplar clones are given elsewhere (Nelson et al. 1981, Isebrands and Nelson 1982, Nelson and Michael 1982, Nelson et al. 1982).

CROWN ARCHITECTURE AND CANOPY DENSITY

Solar energy is the driving force of all photosynthetic processes. Thus, biological yield is intimately related to the light-intercepting characteristics of a crop (Wilson 1979). In trees, as in other crops, light interception is strongly influenced by crown architecture and canopy density. Photosynthetic capacity of leaves is also affected by such variables as position in the crown (Michael et al. 1980), shoot type (Nelson and Michael 1982), and specific leaf weight (Nelson and Ehlers 1981, 1982). Moreover, the economic yield of tree crops such as SRIC poplars is strongly influenced by crown characteristics because of their effects on the utilization potential of the raw material (Crist et al. 1979, Isebrands et al. 1979, Phelps et al. 1982a, 1982b). Therefore, the variables we collectively define here as crown architecture and canopy density (i.e., branch architecture, leaf morphology and distribution, leaf area, and leaf orientation) have a major impact on the quantity and quality of yields

---

[2/] Hereafter Tristis and Eugenei.

from SRIC poplar plantations.

Branch Architecture.--Many factors affect the sequential growth pattern of a poplar crown. Some of these factors are amenable to genetic and/or silvicultural manipulation whereas others are not (Isebrands 1982). For example, branch characteristics of SRIC poplars differ greatly with clone and stand density (Dawson et al. 1976, Isebrands et al. 1977, Nelson et al. 1980a, 1981). However, the ranking of poplar clones for most branch characteristics does not change significantly at different plantation spacings. This lack of a clone-spacing interaction for branch properties (i.e., branch angle) greatly simplifies genetic selection and breeding for crown architecture in poplar (Nelson et al. 1980a, 1981). One illustration of this point is that selected fastigiate genotypes will probably maintain their acute branch angle for a wide range of spacings. Clones with a narrow crown architecture are thought to be advantageous at close spacings because they occupy less space and compete only weakly for light with their neighbors (Burk 1981, Nelson et al. 1981).

Branch architecture of poplar clones also differs with each height growth increment (HGI) (fig. 1) and with position within the HGI (Burk 1981; Isebrands 1982; Isebrands and Nelson 1982). The uppermost first-order branches within each HGI are usually the largest, and their length and diameter decrease basipetally (Jankiewicz and Stecki 1976). The order of branching rarely exceeds third-order in SRIC poplar plantations (Isebrands and Nelson 1982), and live branches are commonly shed (cladoptosis) in the lower crown, particularly in Euramericana clones (Nelson et al. 1981).

Leaf Morphology and Distribution.--In tree crowns leaves of different age, structure, and size; on different shoot types; and at different distances from the main stem have distinctly different physiological properties (Kramer and Kozlowski 1979). These leaf characteristics have important effects on both photosynthetic rate and on the distribution of photosynthate within the tree in SRIC poplars (Isebrands and Nelson 1980; Michael et al. 1980; Nelson and Ehlers 1981, 1982; Nelson and Michael 1982; Isebrands 1982).

SRIC poplars aged 4 and older display their leaves in a complex crown arrangement (fig. 1) encompassing at least three orders of branching and two different shoot types (i.e., long and short shoots)(Isebrands and Nelson 1982). The distribution of leaves, leaf area, and average leaf area per leaf differ with HGI in the tree (table 1). The current terminal

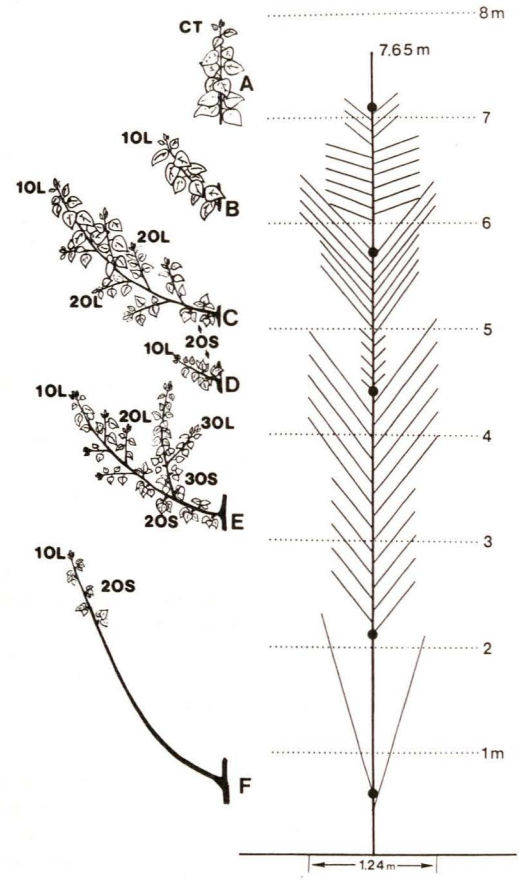


Figure 1.--Schematic of 6-yr-old Populus 'Tristis' grown under SRIC. Each dot on main stem delineates the beginning of an annual height growth increment (HGI). Position A is the current terminal shoot (HGI); B is a first-order long shoot (10L) on HGI 5; C is a first-order branch on HGI 4 with its terminal shoot a long shoot and with second-order long shoots (20L) and second-order short shoots (20S); D is a short first-order branch also on HGI 4 with a terminal shoot ((10L) and with 20S; E is a first-order branch on HGI 3 with 10L, 20L, 20S, and third-order long shoots (30L) and third-order short shoots (30S); and F is a first--order branch on HGI 1 with a terminal shoot (10L) and 20S. Branch length and angles are drawn to scale, except that branches in the field curve upward (from Isebrands and Nelson 1982).

shoot on a 5-yr-old tree has less than 1 percent of the total number of leaves and about 1 percent of the total leaf area. However, these

Table 1.--Average number of leaves, leaf area, and leaf area per leaf within the crown of 5-yr-old SRIC Populus 'Tristis' trees grown at 1.2 m spacing[1/] (from Isebrands and Nelson 1982)

Crown position		Leaves/position		Leaf area/position		Leaf area/leaf
HGI[2/]	CT[3/]	No.	Percent Total	cm^2	Percent Total	cm^2
5		29	<1	1,415	1	47
4		414	6	11,685	11	26
	L	282		8,841		31
	S	132		2,844		22
3		1,528	23	32,728	31	16
	L	1,302		28,534		21
	S	226		4,194		14
2		2,239	34	29,645	29	12
	L	1,988		26,927		13
	S	251		2,718		11
1		2,434	37	29,136	28	11
Total		6,644	100	104,609	100	

1/Weighted averages for nonborder trees are based on proportional stratified sampling of the entire stand.

2/HGI=height growth increment; L=branches >0.6 cm basal diameter; and S=branches <0.6 cm basal diameter.

3/Current terminal.

leaves are the largest on the tree and are attached directly to the main stem. In subsequent HGI's the difference between the percentages of total number of leaves and total leaf area increases dramatically, reflecting a decrease in average leaf size from the upper to the lower portion of the crown.

Knowing the distribution of leaves by HGI alone does not provide a complete indication of the crown's light-intercepting ability. Leaves on a given HGI often occur in several vertical strata or light climates because of the upward growth of branches (table 2). For example, 85 percent of the total number of leaves in 6-yr-old SRIC Tristis occur in the three height strata from 4 to 7 m, and those leaves are on branches attached to HGI's 3, 4, and 5. Thus, leaves within a given light climate often contribute photosynthate to several different parts of the main stem. This difference has major physiological importance because lateral branches normally only contribute appreciable quantities of photosynthate to main stem below their point of attachment (Isebrands 1982). Thus, the rapid growth exhibited by some SRIC poplar clones may be related to the high percentage of their leaf area displayed in favorable light-intercepting positions within the crown.

Table 2.--Distribution of leaves within the crown of a 6-yr-old short rotation intensively cultured Populus 'Tristis' tree grown at 0.6 m spacing by vertical height strata and height growth increment[1/] (from Isebrands and Nelson 1982)

Vertical strata	Total number of leaves		Height growth increment					
			6	5	4	3	2	1
m	No.	Percent	Percent total number of leaves					
7-8	63	4	1	3	-	-	-	-
6-7	539	36	-	16	20	-	-	-
5-6	332	23	-	1	20	2	-	-
4-5	393	26	-	-	6	20	-	-
3-4	108	7	-	-	-	7	-	-
2-3	61	4	-	-	-	3	-	1
<2	-	-	-	-	-	-	-	-
Total	1,496	100	1	20	46	32	-	1

1/Individual tree of average leaf area from subsample.

Although crown position and shoot type are the dominant factors determining leaf size in SRIC poplar clones (Isebrands et al. 1977, Isebrands and Nelson 1982), clonal differences in leaf size are also common (table 3). For example, at the end of 2 years in the field the leaves of NC-9922 were much larger and fewer than NE-298, but total leaf areas of the clones were not significantly different (fig. 2). Clonal differences in specific leaf weight (SLW) are also often substantial; differences in clonal averages may even exceed 20 $g.m^{-2}$ (Isebrands et al. 1977, Gottschalk and Dickmann 1978). SLW usually decreases from the current terminal downward toward the base of the tree (Isebrands et al. 1977, Isebrands and Nelson 1982). In addition, shoot type also has an influence on SLW; long-shoot leaves at similar positions have a higher SLW than short-shoot leaves (Isebrands and Nelson 1982).

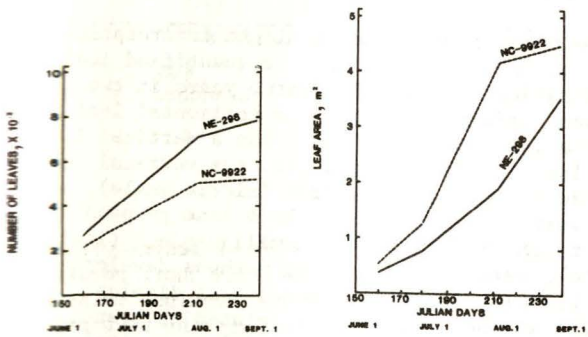


Figure 2.--Seasonal development of number of leaves and leaf area in two, 2-yr-old Populus clones grown under SRIC at 1.2 m spacing (NE-298, P. nigra cv. betulifolia x P. trichocarpa; NC-9922, probably P. deltoides x P. trichocarpa).

The crowns of hybrid poplars grown under SRIC are comprised of a higher ratio of long shoots to short shoots than other poplars (Pollard 1970). The proportion of long and short shoots also differs with clone and age; the proportion of short shoots usually increases as a tree ages (Kozlowski 1971). Five- and 6-yr-old Tristis trees grown under SRIC have 53 to 66 percent of their leaf area on long shoots, with about 95 percent of the long-shoot leaves in the upper three-eighths of the leaf-containing vertical strata. The average long-shoot leaf was 34 cm^2 in area, compared to 19 cm^2 for the average short-shoot leaf (Isebrands and Nelson 1982). The ratio of long shoots to short shoots in a poplar crown has physiological importance. For example, leaves on long shoots of Tristis have higher midseason photosynthetic rates (Nelson and

Table 3.--Seasonal patterns of growth, distribution of leaves, distribution of leaf area, leaf area per leaf, and leaf area index in two, 2-year-old poplar clones grown under intensive culture at 1.2 m spacing

Date[1]/	Height		Diameter		Distribution of leaves		Distribution of leaf area		Leaf area per leaf		Leaf area index[3]/
					Current terminal	Laterals	Current terminal	Laterals	Current terminal	Laterals	
Clone[2]/	9922	298	9922	298	9922 298	9922 298	9922 298	9922 298	9922 298	9922 298	9922 298
	m		cm at 0.3m		- - - Percent - - -		- - - Percent - - -		- - - - cm^2 - - -		$m^2.m^{-2}$
June 9	1.3	1.3	1.5	1.1	5 3	95 97	8 5	92 95	42 21	25 14	0.4 0.3
June 28	1.6	1.5	2.0	1.5	5 4	95 96	10 6	90 94	74 32	38 23	0.9 0.7
July 31	2.4	1.9	3.0	2.2	6 4	94 96	12 8	88 92	172 52	78 26	2.8 1.3
August 29	3.4	2.9	4.3	3.4	8 5	92 95	25 10	75 90	288 87	70 43	3.0 2.4

1/ The 1978 growing season. Each value is the mean of two replications.
2/ The clones were NC-9922, Populus sp., probably P. deltoides x P. trichocarpa; and NE-298, P. nigra x P. trichocarpa.
3/ Mean tree approach assuming no mortality.

Michael 1982) and contribute more photosynthate for wood production than leaves on short shoots. These observations suggest that the high biomass yields for SRIC poplars may be partially explained by the favorable long-shoot/short-shoot ratio in their crowns (Isebrands and Nelson 1982).

Leaf Areas.--SRIC poplar stands have higher leaf areas than natural stands. Leaf area index (LAI) values for 5- and 6-yr-old SRIC Tristis stands at 1.2 and 0.6-m spacings grown under less than optimum conditions were 7.6 and 8.8, respectively (Zavitkovski 1981, Isebrands and Nelson 1982). In addition, LAI's exceeded 15 in 4-yr-old SRIC Tristis grown at 0.6-m spacing, but these trees were grown in small plots and may have had somewhat inflated LAI's because of greater side light penetration (Isebrands et al. 1977).

Clones often differ greatly in LAI (Isebrands et al. 1977, Gottschalk and Dickmann 1978). Moreover, clones also differ significantly in the time required to develop maximum LAI during a growing season (fig. 2, table 3). For example, in the second year NC-9922 and NE-298 had similar leaf areas at the end of the year but most of NC-9922's leaf area was produced during July and most of NE-298's was produced during August.

The high LAI's of SRIC poplar stands result in leaves making up a large portion of the above-ground biomass. For example, in 5-yr-old Tristis grown at 1.2-m spacings, leaves accounted for 10 percent of the total biomass (Isebrands et al. 1979). Leaf biomass can approach 40 percent in young stands planted at close spacings, but that percentage decreases as stands develop and age (Gottschalk and Dickmann 1978).

Stem volume and above-ground biomass of individual trees in SRIC poplar plantations are linearly related to the total leaf area of the tree (Larson et al. 1976, Isebrands et al. 1977, Isebrands and Nelson 1982). Furthermore, stem growth at any particular height is closely related to the cumulative leaf biomass or leaf area above that point (Tadaki 1966, Larson and Isebrands 1972). Although we cannot yet define an "optimum" LAI for SRIC poplar stands, we predict that it will be at least 10. In the stands we've studied we have found no evidence of excessive LAI's that produce negative effects on growth, which is consistent with data from other crops (Watson 1952, Donald 1961). Attaining "optimum" LAI in the SRIC plantation early in the rotation and maintaining it throughout the rotation is important (Isebrands and Nelson 1982). Based on evidence from agronomic crops (Watson 1952, Loomis and Williams 1963, Moss 1975) we suggest that the ability to rapidly attain high LAI early in the growing season and to maintain that leaf area throughout the growing season (i.e., leaf area duration) are important determinants of rapid growth in SRIC poplar stands. Extended green leaf retention in the autumn, a trait in some SRIC poplars, also contributes substantial photosynthate to late season stem and root growth (Nelson et al. 1980b,c, Isebrands 1982, Nelson et al. 1982).

Leaf Orientation.--Because photosynthesis depends on the amount of light, photosynthetic rate per unit leaf area (PgA, $mgCO_2m^{-2}s^{-1}$) is closely related to the effect that the leaf's three dimensional orientation has on light interception (Michael and Dickmann 1982). The importance of leaf orientation on light interception, PgA, and yield has been studied extensively in agronomic crops (Monteith 1965, Vidovic 1974, Austin et al. 1976), but limited information exists for trees.

As part of our study of light interception in SRIC poplars in the field, we quantified leaf orientation during the first 3 years in two clones: Tristis, which has a horizontal leaf display, and Eugenei, which has a vertical leaf display. Leaf azimuth angle, the vertical angle formed by the leaf's midrib (midrib angle), and the vertical angle formed by a line perpendicular to the midrib in the lamellar plane (lamina angle), were measured using methods developed by Max (1975). In poplar clones leaf display angles are not necessarily related to branch angles of the main tree stem, although leaf azimuth and branch azimuth are related (Burk 1981).

In the first growing season, the azimuth angle of a leaf is strongly controlled by its position along the phyllotactic spiral. Midrib angles in both clones were similar. Eugenei's observed vertical leaf orientation was a result of rotation around the midrib axis, i.e., adjustment of the lamina angle (fig. 3). By comparison, Tristis had a minimal deviation of lamina angle from 90° in contrast to Eugenei; this small deviation gives rise to Tristis' horizontal leaf orientation.

Zenith angle (ZA), the angle between a line perpendicular to the leaf's surface and that line's zenith (high point), provides a useful measure of leaf orientation that incorporates all rotations along a leaf's axis into one variable. When ZA = 0, for example, the leaf is horizontal; ZA values increase as leaves become more vertically oriented. During the first growing season mean ZA's were 50° and 20° for Eugenei and Tristis, respectively, and Eugenei had the widest range of ZA values. The same pattern was also observed within the crowns

of 2-yr-old trees; mean ZA's for Eugenei and Tristis were 54° and 21° , respectively.

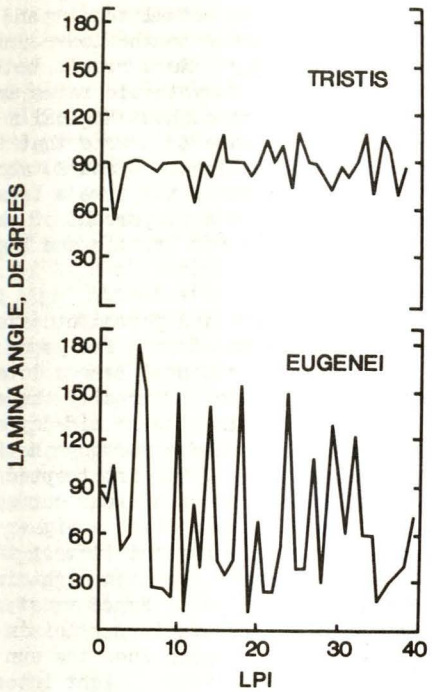


Figure 3.--Lamina angles (the angle between the vertical and a line perpendicular to the leaf midrib in the lamellar plane) for two, 1-yr-old Populus clones (P. tristis x P. balsamifera cv. 'Tristis #1' and P. x euramericana cv. ' Eugenei') by leaf position. LPI 0 (LPI, leaf plastochron index) is the first leaf below the apex attaining a lamina length of 3 cm.

Leaf orientation greatly influenced the distribution of light and photosynthetic activity within the crowns of both clones. Light interception and photosynthesis were concentrated in a few large leaves in Tristis' upper crown due to a high degree of mutual shading in the lower crown. This shading was especially evident after the first growing season. Eugenei's vertical leaf display resulted in less mutual shading and a more even distribution of light and PgA within the crown when compared to Tristis (table 4).

PHOTOSYNTHESIS

Photosynthetic activity varies significantly among the leaves of a poplar tree growing in the field. For example, photosynthesis varies with leaf position, leaf orientation, leaf age, and season.

Table 4.--Within-crown comparison of total leaf area, light interception, and whole-leaf photosynthesis (PgL) for two, 1-yr-old Populus clones[1/]

Clone[2/]	Crown level	Leaf number from base	Leaves	Leaf area	Light interception[3/]	PgL[3/]
			Number	cm^2	μ moles s^{-1}	mg CO_2 s^{-1} x 10^4
Tristis	A	31 - 34	4	148	15 (14)	80 (9)
	B	21 - 30	10	547	60 (54)	470 (55)
	C	11 - 21	10	362	26 (24)	220 (26)
	D	1 - 10	10	177	9 (8)	90 (10)
		TOTAL	34	1,234	110	860
Eugenei	A	30 - 31	2	53	1 (1)	3 (<1)
	B	20 - 29	10	625	37 (38)	360 (43)
	C	11 - 19	9	489	34 (35)	310 (37)
	D	1 - 10	10	310	26 (26)	170 (20)
		TOTAL	31	1,477	98	843

1/ Leaves were measured on 8-8-79.
2/ Clones were Tristis - P. tristis x P. balsamifera cv. 'Tristis #1', and Eugenei - P. x euramericana cv.'Eugenei'.
3/ Values in parentheses are percent of total light interception or PgL.

Establishment Year.--The rate of photosynthesis and the quantity of photosynthate produced by a poplar tree during the first growing season in the field is largely determined by how effectively its leaves capture and utilize available light.

Field measurements within poplar crowns show that single leaf PgA varies greatly due to differences in light interception and leaf age (fig. 4). The net effect of leaf position, leaf orientation, and leaf age on whole-crown photosynthetic rates can be best assessed by measuring photosynthetic rates of leaves in their natural orientation, and then expressing photosynthesis and light interception on a whole-leaf basis for different regions of the crown. This approach allows comparisons to be made between different crown levels within a clone and among different clones.

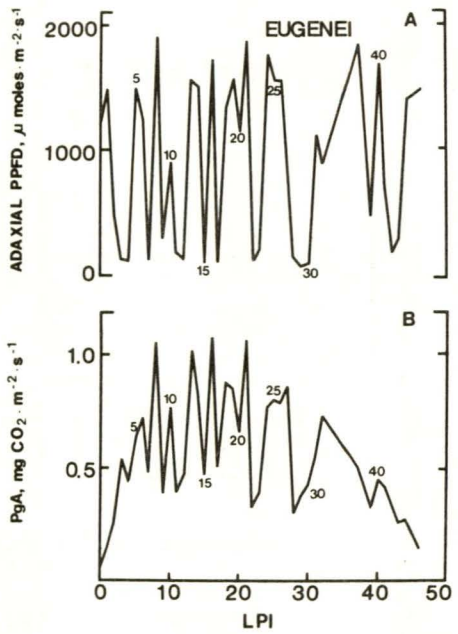


Figure 4.--Adaxial photosynthetic photon flux density (PPFD) and photosynthetic rate (PgA) for a 1-yr-old P. x euramericana cv. 'Eugenei' tree (46 leaves) measured in the field beginning at 10:00 solar time, August 30, 1979.

During the establishment year, leaf area, light interception, and photosynthesis on a whole-leaf basis (PgL, $mgCO_2 s^{-1}$) in both Tristis and Eugenei reached a maximum in the upper-middle crown (level B, table 4). Light interception and PgL in the B level was greater in Tristis than in Eugenei, even though Tristis had less leaf area at that level. This difference is a direct result of clonal variation in leaf display (i.e., light interception strategies).

Tristis' horizontal midcrown leaves capture more light than Eugenei's vertical midcrown leaves, especially when the sun's altitude is high during mid-afternoon. But Eugenei's leaf display produces less mutual shading and allows more light to penetrate to the lower crown levels during mid-day. As a result, both light interception and photosynthetic rates are more evenly distributed throughout Eugenei's crown than in Tristis' (table 4). Note that the two lower crown regions (levels C and D) accounted for 32 and 61 percent of the tree's total intercepted light and 36 and 57 percent of the total crown photosynthesis for Tristis and Eugenei, respectively.

Light interception and photosynthesis in Tristis are concentrated in a few young and highly productive horizontal leaves located in the upper-middle crown. Diurnally these leaves attain maximum illumination at mid-day when they are close to or above photosynthetic light saturation, and most of the intercepted light is concentrated on the upper-leaf surface. Moreover, Tristis leaves reach a higher PgA at light saturation than Eugenei leaves; thus, Tristis leaves can utilize high light intensities better than Eugenei. By contrast, maximum light interception occurs in Eugenei in late morning and late afternoon when the sun is at oblique angles to the tree. Light interception during these peak period occurs on both the upper and lower leaf surfaces. Thus, available light is efficiently utilized because a large number of leaves are illuminated. However, leaves in the lower crown of Eugenei must be photosynthetically responsive to illumination below light saturation in order to benefit from this pattern of light dispersal.

Another difference between the two clones in the first growing season is that the contribution of the lower crown declines rapidly in Eugenei late in the growing season as its leaves senesce. In Tristis the lower crown region remains productive throughout most of the season.

Despite the differences in patterns of light interception, Tristis and Eugenei are about equal in overall photosynthetic efficiency (PE, $mgCO_2$ fixed/μmole of light photons) for the first growing season. At mid-season PE was 7.9 and 8.3 x 10^{-4} mg CO_2 $\mu mole^{-1}$, and in late season PE was 5.4 and 5.7 x 10^{-4} $mgCO_2$ $\mu mole^{-1}$ for Tristis and Eugenei, respectively. The lower values in late season reflect leaf senesence. The similarity in Tristis and Eugenei PE's at both mid- and late season during the establishment year indicate that PE differences alone do not explain observed clonal differences in dry matter production (see Growth Analysis section).

Two-Year-Old Trees.--During the establishment year poplar clones have a simple, single-stemmed crown. However, the complexity of the crown increases in the second growing season with the development of lateral branches. As a result within-tree and between-tree competition for light increases markedly. In the second year, leaf orientation continues to have an important influence on light interception patterns, and single leaf and within-tree photosynthesis. Thus, photosynthetic patterns within the crown continue to mirror those of light interception in both clones. The horizontal leaf display in the upper crown of 2-yr-old Tristis trees resulted in rapid light attentuation within the crown (fig. 5). Light interception was greatest in the large, horizontal current terminal (CT) leaves that are important for height growth and stem wood production (Isebrands 1982). However, the leaves on the upper crown lateral branches of Tristis were still important contributors of photosynthate because they compensated for their low light interception by a large aggregate leaf area (fig. 5). The photosynthetic contribution of the lower crown region was much less than the upper because low light interception was combined with a small aggregate assimilatory area.

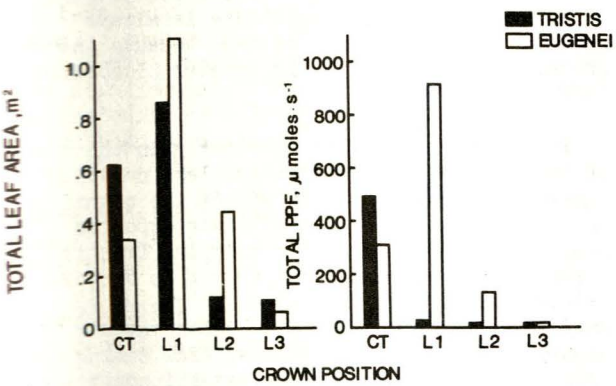


Figure 5.--Total leaf area and total photosynthetic photon flux (PPF) interception of four specific crown regions of individual 2-yr-old P. tristis x balsamifera cv. 'Tristis #1' and P. x euramericana cv. Eugenei trees measured on August 6, 1980. CT = current terminal; L1 = upper lateral branches; L2 = middle lateral branches; and L3 = lower lateral branches.

By contrast, light interception in Eugenei was highest in the upper and middle lateral branches because its vertical leaf display permitted better light penetration to those positions (fig. 5). Leaves on the lower lateral branches received low levels of light and, therefore, had low PgA.

Diurnal patterns of PgL within the crown of 2-yr-old poplars differed with position and with light climate (fig. 6). PgL rates of the CT leaves were the highest in the crown, but PgL rates declined steadily with depth in the crown. Tristis leaves showed a typical bell-shaped curve with peaks at mid-day and that directly reflected changes in photon flux density as the day progressed (fig. 6). However, Eugenei's diurnal pattern (not shown) was more complex because of its vertical leaf display.

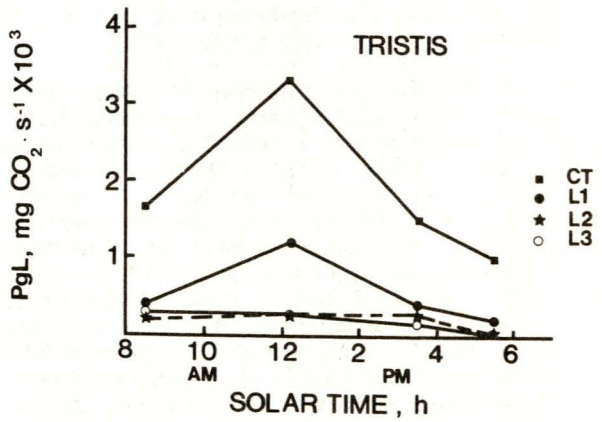


Figure 6.--Diurnal whole-leaf photosynthetic rates (PgL) of four specific crown regions of an individual 2-yr-old P. tristis x balsamifera cv. 'Tristis #1' tree measured on August 12, 1980. CT = current terminal; L1 = fifth lateral branch on height growth increment 1 (HGI 1); L2 = middle lateral branch on HGI 1; L3 = fifth lateral branch from bottom of HGI 1. Each point represents the average PgL of three leaves measured on the same lateral branch.

Three-year-old Trees.--During the third growing season second-order lateral branches develop on each first-order branch in the crown of poplars and add to the complexity of photosynthesis studies. A 3-yr-old poplar crown has four important leaf popluations: (1) the current terminal leaves (i.e. HGI 3), (2) leaves on newly developed first-order lateral branches on HGI 2, (3) leaves on terminal shoots on lateral branches on HGI 1, and (4) leaves on second-order branches arising from the first-order branches on HGI 1.

The general pattern of light interception and PgA that occurs in 2-yr-old trees is also present in 3-yr-old trees. Light interception and PgA rates are highest in the CT (HGI 3) leaves of both Tristis and Eugenei. Leaves on the upper lateral branches are in a more favorable light environment and have higher PgA rates than the middle and lower branches. Young leaves on the current terminals of lower crown (HGI 1) laterals are also capable of high PgA rates if they receive adequate light. A vertical leaf display, such as in Eugenei, allows greater light penetration to the lower laterals resulting in greater PgA rates during midseason compared to a horizontal leaf display, such as in Tristis. However, Tristis retains its lower crown leaves much later into the growing season than Eugenei does. We do not presently know what effect this extended leaf area duration has on total seasonal photosynthate production.

In the third growing season Tristis produces both short shoots (SS) and long shoots (LS) on second-order branches in HGI 1. Photosynthetic rate of LS leaves in mid- to late season is greater than SS leaves because the mean foliage age of the LS is less than the SS; therefore, the LS are more active physiologically than the SS (Nelson and Michael 1982). Both shoot types receive low light levels after midseason and have low PgA rates when located in the lower crown, but the contribution of these shoots may be more important during the early part of the growing season when light levels in the lower crown are greater.

Late-Season Photosynthesis.--Many exotic Populus clones grown under SRIC in Michigan and Wisconsin retain green leaves in the autumn for 2 to 6 weeks after native aspen have lost their leaves. For example, some clones retain their leaves until November 1 or after in northern Wisconsin. Leaves on the terminal shoots of clones exhibiting significant green leaf retention have substantial photosynthetic rates during this period (Nelson et al. 1982). In two such clones PgA rates ranged from 0.16 to 0.36 mg CO_2 $m^{-2}s^{-1}$ during the late-season period. These values reflect significant carbon fixation when compared to net photosynthetic rates for Populus trees growing under favorable conditions (Nelson et al. 1982) and suggest that autumnal retention of green leaves may be an important factor contributing to the rapid growth of poplars under SRIC in a cold temperate climate.

PHOTOSYNTHATE DISTRIBUTION

The complex network of biochemical pathways that make up the photosynthetic process converge into the processes of photosynthate production and partitioning (Wallace et al. 1976). These processes ultimately determine the components of growth and yield in trees and are amenable to study in the field with ^{14}C-tracer techniques (Isebrands 1982).

Establishment Year.--During the establishment year, growth and development of the young poplar shoot depends upon stored photosynthate until mature leaves develop and begin exporting photosynthate to the shoot. During active shoot elongation and prior to budset, upper mature leaves export photosynthate both acropetally to the newly expanding leaves and shoot and basipetally to the stem and roots (fig. 7A). At budset the direction of photosynthate export makes a dramatically basipetal shift. At this time most of the photosynthate is directed downward to the stem and roots and little if any is exported from one mature leaf to another. Lower mature leaves contribute little photosynthate upward during the establishment year (fig. 7B). After budset, export of photosynthate from lower leaves increases to the roots and decreases to the stem. Although the patterns of export are similar after budset from both upper and lower mature leaves, the total quantity of photosynthate is always greater from the upper leaves[3/] because their photosynthetic capacity is greater (Isebrands 1982).

Poplar clones differ distinctly in the time of budset and leaf fall (i.e., leaf duration). These differences greatly affect the quantity and distribution of photosynthate exported from leaves (fig. 7). For example, Tristis normally sets terminal bud from 4 to 5 weeks before the Euramericana clones. Therefore, the shift to basipetal export of photosynthate occurs much sooner in Tristis. The timing of budset in poplar during the establishment year can also be affected when herbicides are used to control weeds (Akinyemiju et al. 1982). Clones susceptible to glyphosate injury often set bud earlier than resistant clones. As a result, photosynthate distribution patterns prematurely shift downward to the stem internodes and roots.

3/ Isebrands, J. G., and N. D. Nelson, unpublished data, 1983.

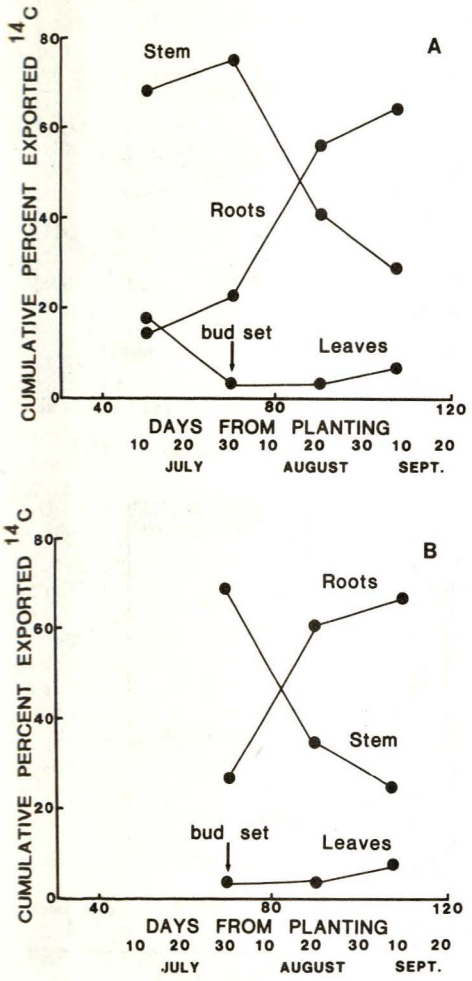


Figure 7.--Cumulative percent of exported ^{14}C from mature leaves of 1-yr-old Populus 'Tristis' shoots grown under SRIC. A. Upper mature leaves treated with ^{14}C. B. Lower mature leaves treated with ^{14}C. Arrows show time at which the current terminal shoot set bud (from Isebrands 1982).

Subsequent Growing Seasons.--During the second and subsequent growing seasons the patterns of photosynthate distribution within the crown are complicated by the addition of lateral branches. The complexity of photosynthate patterns, of course, is related to the intricate photosynthesis patterns discussed earlier. During the second year, as in the first year, shoot growth depends primarily on stored photosynthate until expanding leaves mature. Mature leaves on the current terminal are the most photosynthetically productive leaves in the crown. Carbon fixation declines from the current terminal to the lower lateral branches of the crown (Isebrands 1982).

Photosynthate distribution patterns within second year and older crowns also depends on the various budset and leaf retention times of the current terminal (CT) and lateral shoots (fig. 8). Before CT budset, photosynthate produced by the mature leaves of the CT was exported primarily to the expanding CT leaves above and the elongating CT stem iself (fig. 8A). About 20 percent of the photosynthate produced by the CT leaves was also exported to the stem and roots below. After budset, the quantity exported basipetally to the stem and roots increased, and the quantity exported to the CT itself decreased to about 20 percent. Photosynthate was rarely exported from the CT to the lateral branches.

The patterns of photosynthate distribution from mature leaves on lateral branches were similar regardless of the branch position in the crown (fig. 8B, C, and D). However, the quantity of photosynthate exported and the timing of export from the leaves showed some important differences. Before budset mature leaves of lateral branches exported both acropetally -- to the terminal shoot of the lateral and to the lateral branch itself -- and basipetally to the main stem and roots. Little photosynthate was exported from the lateral branches to the CT shoot or to the other lateral branches. After budset, the quantity of photosynthate exported to the lateral branch itself decreased and the quantity exported to the main stem below and the roots increased. Time of budset differed for various lateral branches in the crown and directly affected photosynthate distribution patterns. For example, budset in the lower and middle lateral branches often occurs 2 to 3 weeks earlier than on the upper lateral branches and 4 to 8 weeks earlier than the CT. Therefore, the basipetal shift of photosynthate export from the lateral branch itself to the main stem and to the roots occurs earlier in the lower portion of the crown than in the upper portion. However, the upper lateral branches generally contribute more photosynthate to the main stem internodes and to the roots than the lower lateral branches (Isebrands 1982).

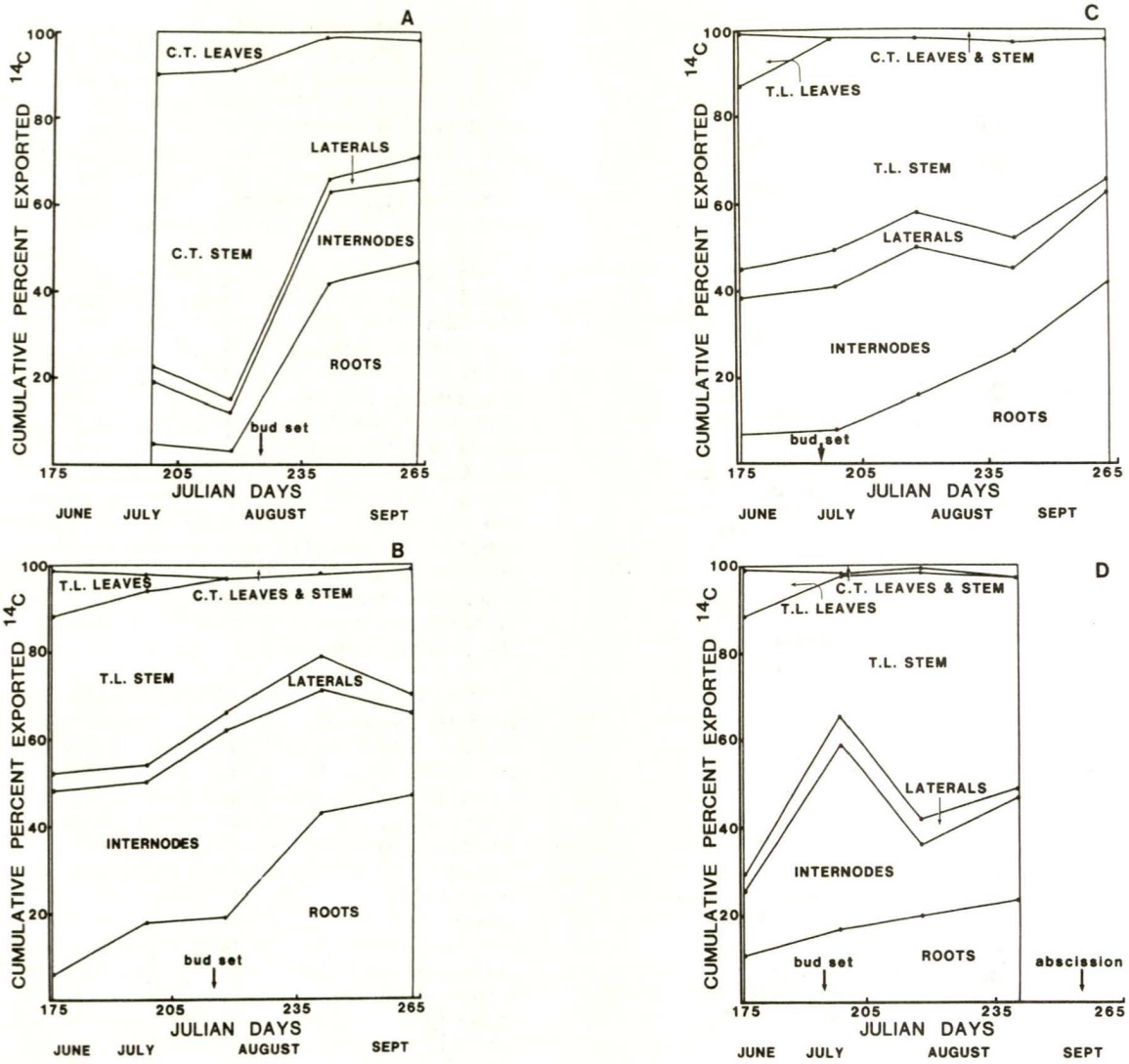


Figure 8.--Cumulative percent of exported ^{14}C from mature leaves at four positions within the crown of 2-yr-old intensively cultured P. 'Tristis" trees treated during the course of the season. Recovery positions include current terminal (CT) leaves, CT stem, treated lateral (TL) leaves, TL stem, lateral branches other than TL, stem internodes of HGI 1, and roots. A. Mature leaves of CT shoot treated with ^{14}C; B. mature leaves of fifth first-order lateral branch from top (L1) of HGI 1 treated with ^{14}C; C. mature leaves of middle first-order branch (L2) on HGI treated with ^{14}C; and D. mature leaves of fifth first-order branch from base (L3) of HGI 1 treated with ^{14}C. Area under the curves estimates the proportion of ^{14}C that would be recovered in a season from a given treatment position. Arrows denote date of budset (A-D) and leaf abscission (D) at each treatment position (from Isebrands 1982).

Although lateral branches in poplar are important sources of photosynthate for wood and root production, little photosynthate from lateral branches is exported to the current terminal shoot. This suggests that lateral branches do not directly contribute to height growth in poplar. Moreover, lateral branches do not export appreciable photosynthate to other lateral branches. Thus, the contributions of lateral branches in poplar are somewhat independent in terms of lateral branch growth. However, the main stem and roots receive localized photosynthate contributions from each of the numerous lateral branches above.

Late Season Photosynthate Distribution.--Poplars that exhibit substantial autumnal leaf retention and late-season photosynthesis also export considerable photosynthate from those leaves[4/]. For example, mature leaves of the Strathglass poplar clone (NE-1) continued to export photosynthate for at least 2 weeks after the first major frost. The photosynthate produced at this time was exported primarily to the stem and roots for storage and growth. There is also evidence that biochemical products produced by leaves in the late season are involved in the process of dormancy induction in terminal buds. These results illustrate the importance of the autumn season in poplar culture and indicate that clones that retain mature green leaves into the autumn may have an advantage over those that do not.

GROWTH ANALYSIS

Growth analyses are quantitative expressions developed to understand biological productivity on the whole-plant level (Evans 1972, Leopold and Kriedemann 1975). They traditionally have been used to compare cultural treatments, varieties, and progenies, and to interpret factors affecting plant growth (Ledig 1974, Wallace et. al. 1976). Growth analysis techniques are also applicable to the study of photosynthate partitioning in plants (i.e., source-sink relations) (Hesketh and Jones 1980, Warren-Wilson 1981). For example, growth analyses can be used to determine whether a poplar clone achieves high yield through high photosynthetic efficiency or through efficient photosynthate partitioning.

Crop yields can be improved by cultural manipulation and/or selection and breeding. However, these methods are most efficient when the physiological processes controlling yield of the crop are understood. One of the most effective ways to achieve this understanding is through studies that integrate physiological methods with growth analyses on the same plants or in the same experiment. But studies that employ such parallel methodology to clarify the relation between physiological characteristics and yield are rare, particularly in forestry.

Growth analyses were conducted in conjunction with photosynthesis and photosynthate distribution studies of Tristis and Eugenei grown under SRIC during the establishment year. The seasonal patterns of several common growth analysis variables are shown for the two clones in fig.9.

4/ Nelson, N. D., and J. G. Isebrands, unpublished data, 1983.

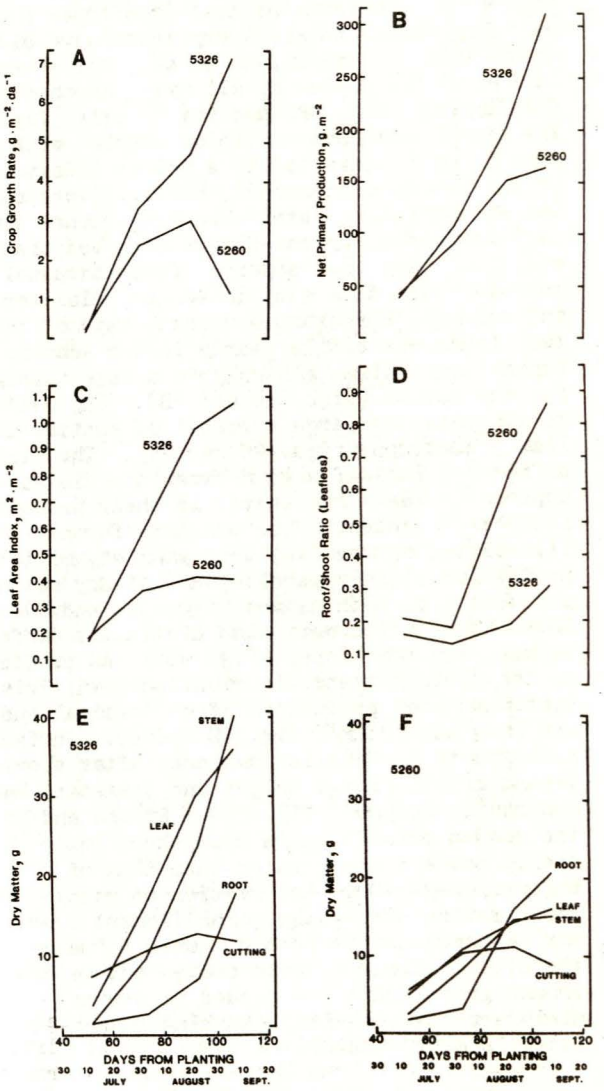


Figure 9.--A comparison during the establishment year of the seasonal patterns of several growth analysis variables for two Populus clones grown under SRIC (NC-5326, P. x euramericana cv. Eugenei; NC-5260, P. tristis x P. balsamifera cv. 'Tristis #1'). A. Crop growth rate (g m^{-2} day $^{-1}$); B. net primary production (g m^{-2}); C. leaf area index ($m^2 \cdot m^{-2}$); D. leafless root/shoot ratio; E. biomass production (g) by component for Eugenei; and F. biomass production (g) by component for Tristis. Total biomass of both above- and below-ground components are included in A and B.

Crop growth rate, the total dry matter accumulated (above and below ground) per unit land area per day, is given in Figure 9A; net primary production, the total dry matter production minus respiration losses is given in Figure 9B. Patterns of leaf area index and root dry matter to shoot dry matter are also shown (fig. 9C and D), as is seasonal accumulation of dry matter by all tree components for Eugenei (fig. 9E) and for Tristis (fig.9F). The growth analysis variables coupled with our physiological data led to a better understanding of the growth patterns of the two clones during the establishment year. Distinct clonal similarities and differences were observed that would not have been apparent from the usual mensurational data such as height, diameter, and volume. For example, growth rate of the two clones was similar early in the season, but Eugenei maintained a high growth rate throughout the season (figs. 9A and 9B). Eugenei's growth rate was large a result of continuous leaf production (figs. 9C and 9E). The large difference in leaf area between the clones apparently was a key factor in their productivity differences. This point is further illustrated by the fact that stem dry matter production closely paralleled leaf dry matter production in both clones (figs. 9E and F). Root-shoot ratios were also distinctly different between the two clones (fig. 9D). As predicted by the photosynthate distribution data, Tristis continued root production after terminal budset and into the autumn (fig. 9D and E). In fact, root growth in Tristis continued after aboveground growth (i.e., height and diameter) had apparently stopped (fig. 9F). At the end of the season Tristis had a root/shoot ratio nearly three times greater than that of Eugenei (fig. 9D). Information on root/shoot ratios during the establishment year may be useful in selecting clones to match the sites. Clearly, both above- and belowground growth data are needed to prevent misinterpretation when comparing clones in establishment studies.

SILVICULTURAL AND GENETIC IMPLICATIONS AND RECOMMENDATIONS

Knowledge gained through physiological investigations such as these can be used to modify silvicultural practices to enhance biomass productivity and in the breeding or selection of new poplar varieties adapted to SRIC systems. The importance of physiological information is evidenced by numerous gains in crop yield made by modern agronomists and horticulturists (Evans 1980). Based on the physiological data accumulated to date, the following practical applications appear evident:

1. Clonal selection and silvicultural practices should emphasize the development of maximum leaf area index for a given spacing throughout the rotation.
2. The major portion of a SRIC poplar tree's leaf area should be in the uppermost crown strata where levels of solar radiation are highest.
3. Clones with erect leaves in the upper crown will probably intercept more light after crown closure than those with horizontal leaves because erect leaves allow for maximum penetration of solar radiation into the lower crown strata.
4. Whereas poplars can usually withstand a single moderate defoliation without appreciable growth losses, massive defoliations by insects or pathogens should be prevented, especially if they are concentrated in the productive upper crown. Defoliation in autumn during the development of vegetative maturity and winter hardiness is particularly harmful.
5. Clones selected for SRIC should attain their maximum rate of leaf area production early in the growing season because such clones generally outgrow those whose maximum rate of leaf area production is not reached until late season.
6. Silvicultural practices and clonal selection should be designed to promote retention of green leaves late in the autumn after bud set, especially in the upper crown. During this time photosynthesis can still take place and much of the photosynthate produced is translocated to the stem and roots. Late-season irrigation and fertilization may promote substantial stem and root growth in clones with late leaf retention.
7. Crown photosynthetic rates are under strong genetic control in poplars and can probably be selected for. However, the cost effectiveness of such a program is currently unknown.
8. Clones with few major lateral branches should be selected for SRIC to promote a high ratio of wood to bark in harvested biomass.
9. Silviculturists and geneticists should emphasize leaf production on the current terminal shoot to increase height growth in SRIC poplars because lateral branches do not contribute photosynthate directly to height growth. However, drastically reducing the leaf area on lateral branches may indirectly affect height

growth through negative effects on carbohydrate reserves and root growth.

10. Narrow-crowned clones with steep branch angles should be used in close-spaced plantations to promote the most efficient use of growing space and maximize interception of solar radiation. Broad-crowned clones with flat branch angles should be used in wide-spaced plantations. The ranking of clones for the most important crown characteristics will not change significantly with spacing.

11. Cultural practices should promote mid-season growth of the terminal leader and uppermost lateral branches because their large, photosynthetically efficient leaves are the major suppliers of photosynthate for stem wood production.

12. A high ratio of long shoots to short shoots in the lower crown of SRIC trees should be promoted for maximum growth.

13. Determinate clones that set bud early in the growing season and thereafter translocate photosynthate to the roots should be planted on harsh, droughty sites where irrigation cannot be supplied. On mesic or irrigated sites where severe moisture deficits are uncommon, indeterminate clones that fully utilize the growing season should be planted.

14. Because the biological optimum rotation for SRIC stand occurs when the relative crown size of trees begins to diminish, stand should not be carried beyond the point where the slope of the linear regression of leaf area per tree (or crown volume) on D^2H declines.

15. To produce the most vigorous coppice stands, SRIC poplar trees should not be harvested immediately after bud set because substantial translocation of photosynthates to the root systems occurs at this time.

These recommendations collectively define our current conception of a superior "ideotype" for a SRIC poplar tree. The recommendations can be used by geneticists to select or "design" improved poplar genotypes and by silviculturists to improve their cultural practices.

ACKNOWLEDGMENTS

The authors wish to acknowledge the technical support of Marynell Redman in data analysis, Lynne Coyer on drafting, and Ron Teclaw on graphics.

LITERATURE CITED

Akinyemkju, O., J. G. Isebrands, N. D. Nelson, and D. I. Dickmann. 1982. Use of glyphoate in the establishment of Populus in short rotation intensive culture. Proc. 19th N. Amer. Poplar Council Annual Meeting, Rhinelander, Wis., July 20-22, p. 161-169.

Austin, R. B., M. A. Ford, J. A. Edrich, and B. E. Hooper. 1976. Some effects of leaf posture on photosynthesis and yield in wheat. Ann. Appl. Biol. 83: 425-446.

Borlaug, N. E. 1977. Forests for people: a challenge in world affairs. Why the challenge? Proc. SAF Nat. Convention, Albequerque, NM. 14 p.

Boyer, J. S. 1982. Plant productivity and environment. Science 218: 443-448.

Burk, T. E. 1981. Crown architecture of intensively cultured Populus: analysis and modeling. Ph.D. Thesis, Univ. of Minn., College of Forestry, St. Paul, Minn. 213 p.

Coyne, D. P. 1980. The role of genetics in vegetable improvement. Sci. Hort.31: 74-88.

Crist, J. B., J. G.Isebrands, and N. D. Nelson. 1979. Suitability of intensively grown Populus raw material for industry. Proc. 16th N. Amer. Poplar Council Annual Meeting, Thompsonville, Mich., Aug. 14-17. p.65-74.

Dawson, D. H., J. G. Isebrands, and J. G. Gordon. 1976. Growth, dry weight yields, and specific gravity of 3 year-old Populus grown under intensive culture. USDA For. Serv. Res. Pap. NC-122, 7 p. North Cent. For. Exp. Stn., St. Paul, Minn.

Donald, C. M. 1961. Competition for light in crops and pastures. In: Mechanisms in biological competition. Symp. Soc. Exp. Biol. 15: 282-313.

Donald, C. M. 1968. The breeding of crop ideotypes. Euphytica 17: 385-403.

Evans, L. T. 1972. The quantitative study of plant growth. Blackwell Sci. Publications, UK. 733 p.

Evans, L. T. 1980. The natural history of crop yield. Amer. Sci. 68: 388-397.

Freeman, S. M. 1975. Tracer techniques for plant breeding. Int. Atomic Energy Agency. Vienna. 117 p.

Gottschalk, K. W., and D. I. Dickmann. 1978. First year growth, biomass yield and leaf area development of four intensively-cultured Populus clones in southern Michigan. In: P. E. Pope (ed.), Proc. cent. hardwoods conf. II, W. Lafayette, IN, 11/14-16,p.140-158.

Hesketh, J. D., and J.W. Jones. 1980. Integrating traditional growth analysis techniques with recent modeling of carbon and nitrogen metabolism. In: J. D. Hesketh and J. W. Jones (ed.), Predicting photosynthesis for ecosystem models. CRC Press, Boca Raton, FL. p. 51-92.

Isebrands, J. G. 1982. Toward a physiological basis of intensive culture of poplars. Proc. 1982 TAPPI R&D Conf., Asheville, N.C. Aug. 29-Sept. 1. p. 81-90.

Isebrands, J. G., and N. D. Nelson. 1980. Apportionment of ^{14}C-labeled photosynthate within intensively cultured Populus trees. Plant Physiol. Ann. Meet. Suppl. 65: 121 (Abst.)

Isebrands, J. G., and N. D. Nelson. 1980. Photosynthate distribution within short rotation intensively cultured Populus clones during the establishment year. Proc. N. Amer. For. Biology Workshop, Edmonton, Alberta, Canada, Aug. 11-13, 1980. p. 150 (Abst.)

Isebrands, J. G., and N. D. Nelson. 1982. Crown architecture of short-rotation intensively cultured Populus. II. Branch morphology and distribution of leaves within the crown of Populus 'Tristis' as related to biomass production. Can. J. For. Res. 12: 853-864.

Isebrands, J. G., L. C. Promnitz, and D. H. Dawson. 1977. Leaf area develolopment in short rotation intensively cultured Populus plots. Proc. TAPPI Forest Biology Wood Chemistry Conf., Madison, Wis.. June 20-22, p. 201-210.

Isebrands, J. G., J. A. Sturos, and J. B. Crist. 1979. Integrated utilization of biomass-a case study of short-rotation intensively cultured Populus raw material. TAPPI 62: 67-70.

Jankiewicz, L. S., and Z. J. Stecki. 1976. Some mechanisms responsible for differences in tree form. In: M.G.R. Cannell and F. T. Last (ed.), Tree physiology and yield improvement. Academic Press, New York, N.Y. p. 157-172.

Kozlowski, T. T. 1971. Growth and development of trees. Vol. I. Academic Press, New York, N.Y. 443 p.

Kramer, P. J., and T. T. Kozlowski. 1979. Physiology of woody plants. Academic Press, New York, N.Y. 811 p.

Larson, P. R. 1969. Wood formation and the concept of wood quality. Yale Univ. For. Bull. No. 74, 54 p.

Larson, P. R., and J. G. Isebrands. 1972. The relation between leaf production and wood weight in first year root sprouts of two Populus clones. Can. J. For. Res. 2: 98-104.

Larson, P. R., R. E. Dickson, and J.G. Isebrands. 1976. Some physiological applications for intensive culture. In: Intensive plantation culture: five years research. USDA For. Serv. Gen. Tech. Rep. NC-21. p. 10-18. North Cent. For. Exp. Stn., St. Paul, Minn.

Ledig, F. T. 1974. Concepts of growth analysis. Proc. 3rd N. Amer. For. Biol. Workshop. Ft. Collins, Col., Sept. 9-12. p. 166-182.

Ledig, F. T. 1975. Increasing the productivity of forest trees. In: B.A. Thielges (ed.). Forest tree improvement - the third decade. Louisiana State Univ., Baton Rouge, p.189-208.

Leopold, A. C., and P. E. Kriedemann. 1975. Plant growth and development. McGraw Hill. New York. 545 p.

Loomis, R., and W. Williams. 1963. Maximum crop productivity: an estimate. Crop Sci. 3: 67-72.

Max, T. 1975. Crown geometry, light interception, and photosynthesis of selected Populus x euramericana clones: a modeling approach. Ph.D. Thesis. Iowa State Univ., Ames, Iowa. 126 p.

Michael, D., and D. I. Dickmann. 1982. Effects of leaf orientation on light interception and photosynthesis in two intensively grown Populus hybrids. Proc. N. Amer. For. Biol. Workshop, Lexington, Ky. July 26-28 (Abst. No. 42)

Michael, D., D. I. Dickmann, and N. Nelson. 1980. Seasonal and diurnal patterns of photosynthesis and leaf conductance in the first year stands of two Populus clones grown under intensive culture. Proc. N. Amer. For. Biol. Workshop, Edmonton, Alberta, Canada, Aug. 11-13. p. 149 (Abst.)

Monteith, J. L. 1965. Light distribution and photosynthesis in field crops. Ann. Bot. 29: 17-37.

Moss, D. N. 1975. Studies on increasing photosynthesis in crop plants. In: R. Burris and C Black (ed.), CO_2 metabolism and plant productivity. University Park Press, Baltimore, MD. p. 31-44.

Nasyrov, Y. 1978. Genetic control of photosynthesis and improving of crop production. Ann. Rev. Plant Physiol. 29: 215-237.

Nelson, N. D., and P. Ehlers. 1981. Comparative photosynthesis within two poplar clones grown in growth room, greenhouse, and field. Plant Physiol. Ann. Meet. Suppl. 67: 93 (Abst.)

Nelson, N. D., and P. Ehlers. 1982. Photosynthetic physiology of hybrid poplar clones grown in different experimental environments. Proc. N. Amer. For. Biol. Workshop, Lexington, Ky. July 26-28 (Abst. No. 45)

Nelson, N. D., and D. Michael. 1982. Photosynthesis, leaf conductance, and specific leaf weight in long and short shoots of Populus 'Tristis #1' grown under intensive culture. Forest Sci. 28: 737-744.

Nelson, N. D., T. Burk, J. G. Isebrands, and A. R. Ek. 1980a. Clone and spacing effects on branch characteristics of short rotation intensively cultured Populus. Proc. 1st N. Cent. Tree Imp. Conf., Madison, Wis., Aug. 22-23, p. 74-85.

Nelson, N. D., T. Burk, and J. G. Isebrands. 1981. Crown architecture of short-rotation intensively-cultured Populus. I. Effects of clone and spacing on first-order branch characteristics. Can. J. For. Res. 11: 73-81.

Nelson, N. D., D. I. Dickmann, and K.W. Gottschalk. 1982. Autumnal photosynthesis in short-rotation intensively cultured Populus clones. Photosynthetica 16: 321-333.

Nelson, N. D., P. Ehlers, and D. Michael. 1980b. Late season photosynthesis in exotic intensively-cultured Populus clones. Plant Physiol. Ann. Meet. Suppl. 66: 50 (Abst.)

Nelson, N. D., P. Ehlers, and D. Michael. 1980c. Autumnal photosynthesis in short-rotation intensively-cultured (SRIC) Populus. Proc. N. Amer. For. Biol. Workshop, Edmonton, Alberta, Canada, Aug. 11-13. p. 147 (Abst.)

Phelps, J. E., J. G. Isebrands, and D. Jowett. 1982a. Raw material quality of short rotation intensively cultured Populus clones I. A comparison of stem and branch properties at three spacings. IAWA Bull. 3: 193-200.

Phelps, J. E., J. G. Isebrands, and N. D. Nelson. 1982b. Utilization potential of SRIC poplar raw material -- a status report. Proc. 19th N. Amer. Poplar Council Annual Meeting, Rhinelander, Wis., July 20-22. p. 134 (Abst.)

Pollard, D. F. W. 1970. Leaf area development on different shoot types in a young aspen stand and its effect upon production. Can. J. Bot. 48: 1801-1804.

Tadaki, Y, 1966. Some discussions of the leaf biomass of forest stands. Gov. For. Exp. Stn. Tokyo Bull. 184: 135-161.

Vidovic, J. 1974. Effect of the change of leaf angle arrangement on productivity of maize (Zea mays L.) stands. Biol. Plant. 16: 174-183.

Warren-Wilson, J. 1981. Analysis of growth, photosynthesis and light interception for single plants and stands. Ann. Bot. 48: 507-512.

Watson, J. 1952. The physiological basis of variation in yield. Adv. Agron. 4: 101-145.

Wilson, D. 1979. Breeding for morphological and physiological traits. In: K. J. Frey (ed.), Plant breeding II. Iowa State Univ. Press, Ames, Iowa, p. 233-290.

Wallace, D., M. Peet, and J. Ozbun. 1976. Studies of CO_2 metabolism in Phaseolus vulgaris L. and applications in breeding. In: R. Burris and C. Black (ed.), CO_2 metabolism and plant productivity, University Press, Baltimore, Md. p. 43-58.

Zavitkovski, J. 1981. Structure and seasonal distribution of litterfall in young plantations of Populus 'Tristis#1'. Plant and Soil 60: 409-422.

RECENT ADVANCES IN RESEARCH OF SOME PEST PROBLEMS OF HYBRID POPULUS IN MICHIGAN AND WISCONSIN

Lincoln M. Moore and Louis F. Wilson[1]

Abstract.--Hybrid Populus clones were examined for impact from and resistance to attack from several insects and diseases. Cottonwood leaf beetle, poplar-and-willow borer, and Septoria canker were most injurious. The spotted poplar aphid and poplar-gall saperda, even when abundant, caused only minor impact. The tarnished plant bug, a newly identified pest of Populus, injured young trees near agricultural areas. Hybrid clones show a wide range of susceptibility to pests and provide exceptional breeding material for pest-resistant trees.

Hybrid Populus plantings are proving to be particularly vulnerable to insect and disease pests. At least 150 insects and 50 or more diseases are potentially injurious. The insect pests are mostly native ones that feed on aspens and cottonwoods but are equally at home on hybrids grown for intensive culture. For nearly 10 years, the North Central Forest Experiment Station has conducted or supported research on several insects and diseases of hybrid poplars at the Harshaw Farm, Rhinelander, WI; at the Boscobel Nursery and the University of Wisconsin at Madison; and on land owned by the Packaging Corporation of America at Manistee, MI. Results of some of these studies were summarized in an earlier report (Wilson 1979).

Since the last report we have been studying some of the same pests and a few new pests. The most investigated pests include: poplar-and-willow borer (Cryptorhynchus lapathi L.), cottonwood leaf beetle (Chrysomela scripta Fab.), tarnished plant bug (Lygus lineolaris Palisot de Beavois), Septoria leaf spot and canker (Septoria musiva Peck), poplar-gall saperda (Saperda inornata, Say), and spotted poplar aphid (Aphis maculatae Oestlund). We have summarized these studies and a study on simulated insect injury in this report, emphasizing the results during 1979-1982.

[1]Research Forest Entomologists, USDA Forest Service, North Central Forest Experiment Station, East Lansing, MI.

RESEARCH RESULTS

Poplar-and-Willow Borer

The poplar-and-willow borer is the most important boring insect in intensive culture hybrid poplar plantings in the Lake States. It readily attacks young sapling and pole-size trees. Heavy attacks can cause growth loss, stem breakage, tree deformity, and mortality.

The most heavily attacked planting we have studied so far is in a stand of Raverdeau and NE-353 poplars in Benzonia Co., MI, owned by Packaging Corporation of America (PCA). The Raverdeau was established from rooted stock and planted in rows adjacent to NE-353 established from 40 cm cuttings the same year.

Both the Raverdeau and NE-353 clones were attacked by the borer, but the Raverdeau was injured first and more severely. This probably occurred because Raverdeau trees were faster growing and reached a diameter susceptible to attack quicker than NE-353. Morris (1980) and Moore et al. (1982a) found that trees were usually free from attack until they grew to 2.0 cm at the base. All first-year attacks, as a consequence, tended to be within 30 cm of the base. But, as trees aged, borers attacked more often and higher on the tree.

After three growing seasons, nearly half of the Raverdeau and a quarter of the NE-353 trees were attacked. By then only 10 out of 1,400 trees had died or broken over. Data from other locations, however, indicate that more damage is

possible because borer-infested trees are particularly susceptible to breakage from wind or ice (Morris 1980).

We examined poplar-and-willow borer attacks in a stand at three levels of Populus biomass densities at Rhinelander, WI, in 1981. The clone densities were at 5,000, 10,000, and 15,000 T/ha. Poplar-and-willow borer was counted on three P. x euramericana clones: NC 5323, 'Canada Blanc'; NC-5326, 'Eugenei'; and NC-5377, 'Wisconsin #5' at these three densities. The preliminary data (table 1) were too variable to indicate whether or not density is related to borer attack.

Table 1.--Poplar-and-willow borer attacks on three P. x euramericana clones at three biomass densities

Clone	Mean attacks at densities (T/ha) of: 5,000	10,000	15,000	All
'Canada Blanc'	7.2	1.8	15.6	8.2
'Eugenii'	4.8	2.8	4.8	4.1
'Wisconsin #5'	9.0	3.6	7.0	6.5
Mean Total	7.0	2.7	9.1	6.3

Cottonwood Leaf Beetle

In recent years, the cottonwood leaf beetle has become the number one defoliator in certain Wisconsin and Minnesota plantings of hybrid Populus. Hybrid selections of 12 standard clones and tissue-cultured subclones of P. x euramericana grown at the Boscobel Nursery in Wisconsin gave us an opportunity to study the insect in greater detail.

Cooperators at the University of Wisconsin set out to study the beetle's biology and ecology, to determine its host preference for feeding, and to study the subsequent utilization of Populus tissues as a nutrient source for its growth and development.

The cottonwood leaf beetle (CLB) is a highly prolific insect--females produce an average of 510 eggs (Burkot and Benjamin 1979). In southern Wisconsin four generations occurred between May and September, each generation appearing at about 20-day intervals. After the last generation the adults overwintered in the leaves and debris beneath the host trees.

Larvae, soon after hatching, fed gregariously and skeletonized the foliage. As they aged, they spread out and devoured entire leaves. When food became scarce, the beetles consumed young bark of shoots on the tree tops. Adult beetles also fed on the foliage, adding to the injury.

Life-table studies suggest that predators and parasites kill many CLB's but not enough to keep the population below economic thresholds. The most significant biological control agents found were: Coleomegilla maculata DeGeer, which consumed 25 percent of the eggs; and Shizonatus latus Walker, a pteromolid parasite which destroyed 26 percent of the pupae. The pentatomids Podisus maculiventris Say and Perillus bioculatus Fab., and lacewing and syrphid flies accounted for a small percentage of the young-larval mortality. Few natural enemies attacked the larvae mainly because of the defensive secretion they emit when disturbed or attacked.

Starvation was another main cause of death; four generations of beetles quickly over-ran their hosts and rapidly defoliated them. Population increases showed a potential in excess of 25, 18, and 8 times for the first three generations respectively, which produced millions of beetles in the nursery each season.

Taxonomically the genus Populus is subdivided into five sections. The three major ones are Leuce, Aigeiros, and Tacamahaca. In host preference tests between clones of these three sections, CLB adults would not feed on hybrid clones from the Leuce section (table 2).

Table 2.--Populus clones and CLB feeding preference

Clone	Defoliation Level[1/]	Sectional Composition[2/]
	(percent)	
'Crandon'	0	100% Leuce
NE-1	22	50% A., 50% T.
NE-299	33	50% A., 50% T.
DN-21	41	100% Aigeiros
NC-5260	47	100% Tacamahaca
NE-298	49	50% A., 50% T.
NE-372	51	25% A., 75% T.
NE-387	52	25% A. 75% T.
'Wisconsin #5'	65	100% Aigeiros
NE-252	66	50% A., 50% T.
NE-386	68	25% A., 75% T.
NE-375	78	100% Aigeiros

[1/] Level of defoliation reported by Caldbeck et al. (1978).

[2/] A. = Aigeiros; T. = Tacamahaca

We expected the beetle to reject the Leuce foliage because the aspens and white poplars in this section are not normally hosts of the CLB

(Harrell et al. 1981). Beetles occasionally nibble these hosts but barely injures them because the foliage was generally unsuitable for their development (Caldbeck et al. 1978, Wilson 1979).

The adults showed an intermediate preference for Aigeiros clones and a high preference for all clones with Tacamahaca parentage. Leaf extractions and bioassays indicated that one or more sugars may be responsible for these preferences. Such differences suggest that increasing the Aigeiros component in future hybrids might make them more resistant to the CLB.

By examining CLB's when exposed to a single tissue-cultured clone (P. x euramericana 'Wisconsin #5'), cooperators found that moisture content and foliage affected the beetles' development and behavior (Harrell et al. 1982). Larvae fed equally on all leaves with water contents greater than 73 percent but did not feed on leaves with less than 70-percent water. In the latter case, the larvae fed on the shoots instead of the leaves. Adults, however, prefered the more succulent, high-water content leaves in the upper crown (table 3).

Table 3.--Adult cottonwood leaf beetle feeding preference with respect to P. x euramericana leaves of different maturity

Leaf position on stem	Mean leaf water content	Mean leaf consumption
	(percent)	(mm^2 ± S.E.)
1 (youngest)	80.9	57.1 ± 10.33
2	80.2	32.7 ± 11.80
3	76.8	2.1 ± 1.01
4 (oldest)	75.2	0.6 ± 0.33

Larvae were affected by foliage. They developed in an average of 13.5 days on immature foliage and in 14.6 days on mature foliage. Of even greater significance was insect size relative to foliage maturity. Larvae reared on immature foliage yielded prepupae weighing 42.3 mg in contrast to the prepupae weighing 33.5 mg from those reared on mature foliage.

These results suggest that leaf water content or some other leaf constituent that varies with water content has an important influence on the feeding of CLB's and the damage these insects cause. Other plant factors that may be important in reducing CLB feeding and development on the more mature leaves include a lower nitrogen content and higher amounts of fiber and tannins. Additional studies are needed to determine the importance of each of these plant factors so that the information can be utilized in developing resistant poplar clones.

Tarnished Plant Bug

In 1978 an unknown agent began injuring young hybrid Populus trees planted on the Harshaw Forestry Research Farm near Rhinelander, WI. Each summer thereafter, lesions developed on the stems and occasionally on short branches, growing tips, and leaf petioles of certain clones of newly planted and 1- and 2-year old Populus grown from cuttings. The stem lesions occurred in the middle or upper portion of young trees; the injured areas sometimes calloused over but frequently stems were girdled or broken above the injury. The injured area was technically a split-stem lesion and when fully formed consisted of an irregular elongate split with a swollen flared area of necrotic bark and xylem tissues around the stem (fig. 1). Mature lesions ranged from less than 0.5 cm to 5 cm long.

Figure 1.--Split-stem lesion on Populus caused by tarnished plant bug

Initial dissections of lesions for insects and isolations for pathogens provided no clue to the cause of the injury (Sapio et al. 1982). A possible insect and disease association, however, was indicated after the application of malathion,

which eliminated most insects at the spray site. New lesions continued to form in an unsprayed area after the treatment but only a few formed in the treated area. In 1981 we set out to determine the causal agent of the lesion, incidence of injury among various Populus clones, and the best ways to prevent it.

Many field and greenhouse tests ultimately identified the causal agent as the tarnished plant bug, normally a destructive pest of agricultural and fruit crops such as alfalfa, cotton, beans, apple, and peach. Though many lygus bugs closely related to the tarnished plant bug (TPB) transmit pathogenic fungi to plants, the TPB did not appear to induce the lesions by vectoring pathogens. Instead, it may have caused lesions through enzymatic activity from its saliva.

TPB's fed on and caused lesions on various clones of hybrid poplar as well as quaking and big tooth aspen. An examination of 20 clones at the Harshaw Farm revealed that NE-298, NE-386, NE-387, and NC-9921 appeared to be consistently the most susceptible. Clones NE-299 and NC-9922 appeared totally resistant in a clonal trial, but were moderately lesioned in other locations. We suspect this may have been because the TPB preferred these clones over less desirable ones or because it lacked other suitable food sources nearby. All clones are probably somewhat susceptible to TPB injury when food choice is limited. For instance, clone NE-375 which appeared highly resistant, developed lesions when caged with TPB's. In fact, it developed more lesions than susceptible clone NC-9922.

Field tests further suggested that Populus resistance is tempered somewhat by the trees' proximity to preferred food sources such as horseweed and fleabane--two weeds common at Harshaw Farm. Also, when white dutch clover was used as a cover crop, it seemed to attract the TPB's and prevent injury to Populus. White dutch clover is one of the TPB's favorite hosts and apparently highly preferred over Populus.

During the first two growing seasons after planting, Populus hybrids showed the highest risk for the TPB lesion. TPB's rarely fly more than 2 m above the ground, so the succculent tissue of the mainstem of Populus is usually well out of reach after the second growing season. The TPB may also feed on the lower twigs but its impact is inconsequential to Populus growth and biomass production.

Cover cropping may minimize TPB injury if properly used or integrated with pesticides. Studies on the management of horseweed, white dutch clover, alfalfa, and other associated treatments are still needed before conclusions can be drawn. Horseweed is somewhat resistant to glyphosate herbicide and its presence seems to be beneficial in lowering incidence of lesions. Perhaps some flowering weeds should be maintained near Populus plantings to entice TPB's away from the trees. Such weeds also encourage parasites that are drawn to the pollen to feed.

The TPB can be suppressed by one or more applications of suitable insecticides. Ultra-low volume malathion has been successful at 9.7 oz. actual insecticide per acre when used in alfalfa fields. It appears to be useful only for short-term suppressions, however, because emigrating adults quickly repopulate an area. Also, there are at least three generations of the TPB in Wisconsin, which further complicate matters.

All in all, perhaps an early season spray integrated with an appropriate weed-management program might successfully control the tarnished plant bug in young Populus stands.

Septoria Leaf Spot and Canker

Septoria is a serious disease on the leaves and stems of hybrid poplars of all ages. This fungus causes small necrotic spots on the leaves; heavy infection usually causes premature leaf drop. Cankers form on the mainstem and branches. Coalescent cankers reduce growth, cause stem breakage, and kill trees. Spores of this disease are carried by wind and rainsplash to leaves, stems, and branches where infection occurs.

In 1979 some nursery stock and a Populus plantation adjacent to the PCA nursery were infected by Septoria. Becoming heavily cankered, the plantation was cut in 1980 for firewood and the stumps were allowed to resprout. In 1981, these sprouts were also cankered and additional nursery stock was infected.

To study Septoria, we set out to determine the severity and site of Septoria infection of first-year coppice and to determine the most susceptible clones in the nursery stool beds.

After coppicing, there were an average of 34 sprouts per stump (range 2-84), and 52 percent of these sprouts were infected in the fall of 1981. All but one of the 75 stumps examined had at least one cankered sprout. Septoria canker was more prevalent on lower stems at leaf petioles and buds as compared to elsewhere on the stems. Densely spaced sprouts encouraged Septoria infection by trapping infected leaves and retaining a moist micro-environment ideal for infection. Infected leaf debris around the stumps also contributed to pathogen retention, spread, and disease severity (Moore et al. 1982b). The severe Septoria infection in the plantation was the result of planting highly susceptible clones.

Nursery stool beds may be even more vulnerable to Septoria than plantations because they are more closely spaced and thus retain higher moisture. Overhead irrigation probably further increases infection. Nearly two-fifths of the clones in the nursery were heavily infected with Septoria. All the P. maximowiczii crosses were heavily infected. This group has been highly susceptible in inoculation tests (Waterman 1954), and cankers also have been found on this species in the eastern U.S. As the male parent, P. trichocarpa appeared in 11 of the 19 highly susceptible crosses at PCA and in none of the resistant clones, indicating that it may contribute to clonal vulnerability to Septoria. P. trichocarpa crosses (as the male parent) have been rated more susceptible to Septoria than P. deltoides (as the female parent) (Waterman 1954). Six of our infected P. deltoides crosses were ones with P. trichocarpa and were among the heaviest cankered.

This study indicates that Septoria canker and leaf spot is certainly one of the most damaging diseases of hybrid poplars in Michigan and, unless managed, can limit the usefulness of susceptible clones. Nursery stock and plantation coppice are infected by spores from infected leaf debris in early spring. Removing this debris is one way to control Septoria. However, local screening of clones for resistance and planting these resistant clones is the most promising long term control strategy in areas where Septoria is known to be a problem. Until this screening is complete, land managers should be aware of the potential hazard from Septoria, if highly susceptible clones are planted. Hybrid poplars with P. trichocarpa, P. laurifolia, or P. maximowiczii as one of the parents were the most susceptible to Septoria and probably should not be planted where this fungus is known to be present.

Poplar-gall Saperda

The poplar-gall saperda attacks the stems and branches of natural and hybrid Populus. Larval feeding forms a swelling that weakens the stems and branches, sometimes causing them to break or die.

During our investigations in PCA plantings in Michigan, we had an opportunity to study the incidence of saperda attacks and the insect's impact in an outplanting of 5-foot tall Populus whips of mixed clones planted in the spring of 1979. The planting was set out in a clearing surrounded by saperda-infested aspens that apparently permitted rapid infestation of the whips.

In the first season of attack, more than 60 percent of the whips were galled by the beetle. Average attack was nearly 2 galls per tree (range 0-12 galls/tree). By the end of the season, 2.6 percent trees died from galls near the base of the trees. Another 7.5 percent were top-killed from galls higher on the stem. Attacks the second year gave the tree another two galls per tree, but nearly 30 percent were on the branches. By the end of the second season, mortality rose by 0.2 percent to 2.8 percent and top-kill increased by 1.5 percent to 9.0 percent. Height differences between galled and ungalled trees were statistically insignificant after the second year.

These data suggest that the poplar-gall saperda does not appear to be a threat to young trees up to the attack level of an average of four galls per tree. Mortality of 2.8 percent after 2 years is not much more than might be expected from most other causes and certainly only a minor concern for biomass production. Almost no additional trees died after the second year mainly because old-galled areas become overgrown by the tree. This also minimized breakage as the tree is strengthened by the new growth. Most top-killed trees resprouted new shoots and quickly regained most of the lost height the following season, suggesting that breakage has little impact on biomass production. So far, this insect has not proved to be a destructive pest and further research is needed with many Populus clones under variable growing conditions before its real impact can be determined.

Spotted Poplar Aphid

The spotted poplar aphid feeds on the terminal shoots of various species of Populus. Clustering in tightly nested colonies, these aphids en masse often cover the entire growing tip and first two or three ranks of leaves during mid and late summer.

This insect has been a perennial pest in the PCA nursery in recent years. We rated all the clones in the nursery according to their susceptibility to this aphid and examined its impact on growth. We also tested two insecticides for controlling the aphid.

Clones of Populus x jackii were the most susceptible to the aphid, having the most numerous attacks and largest aphid colonies. The five next most susceptible clones were NE-19, NE-41, NE-209, NE-298, and NE-360. Resistant clones were NE-19, D-38, I-4551, NE-375, NE-224, and NE-238. None was attacked in the nursery. All other clones were attacked by at least a few colonies and varied from a trace to a moderate infestation. When heavily infested stool-bed suckers were compared to non-infested ones within clones of P. x jackii, we found no significant growth differences at the end of the growing season.

Two insecticidal soaps were tested on aphid colonies on four Populus clones at recommended full strength (1.0%) and half-strength (0.5%) dosages. The chemicals tested were Safer insecticidal soap concentrate containing 50.5 percent potassium salts of fatty acids, and a 10 percent mono-L-pesticide developed in the Department of Biomechanics at Michigan State University. The treatments were tested at the PCA nursery and at Morin's Nursery at Manistee, MI.

Both insecticides and dosages controlled the aphids about equally on three of the clones--DN-22, DN-28, and Raverdeau (table 4). Control was slightly less effective on DN-55 colonies.

Table 4.--Control of spotted poplar aphid on cottonwood clones with insecticidal soaps

Populus clone	Insecticide	Dosage	Aphids controlled
		(percent)	(percent)
DN-22	Safer	0.5	88
	Safer	1.0	91
	MSU	0.5	89
	MSU	1.0	94
DN-55	Safer	0.5	76
	Safer	1.0	77
	MSU	0.5	86
	MSU	1.0	84
DN-28	MSU	0.5	96
	MSU	1.0	91
Raverdeau	MSU	0.5	93
	MSU	1.0	88

We concluded from these tests that the insecticidal soaps gave sufficient control to disrupt the colonies for the remainder of the season. However, we would not recommend MSU's formula because it caused some burning of foliage when applied on sunny days, although it controlled adequately.

Insect Damage Simulation

Cooperators at Michigan State University completed tests on the effects of simulated insect damage of hybrid Populus in a study planting at Rhinelander, WI (Bassman et al. 1982). Insect defoliation and girdling/boring was simulated to assess potential growth impact under nursery conditions. Partial defoliation in several patterns was tested both early and late in the growing season. Clones tested were: NE-298 (P. nigra var. betulifolia x P. trichocarpa); NC-5260 (P. tristis x P. balsamifera) and NC-5351 (Populus sp.).

Trees that had defoliation levels of 40 percent were identical in height growth to non-defoliated trees showing that moderate defoliation is not cause for concern even in such young trees. Further, the young trees appeared to sustain 2 years of 40-percent defoliation without significant growth loss as long as favorable growing conditions were maintained. Defoliation levels of 75 to 80 percent, however, consistently produced significant height growth reductions on the order of 20 percent. Complete defoliation was not tested because normal practice would be to apply insecticides if defoliation appeared likely to become that severe.

Timing of defoliation in the growing season did not seem to be particularly important for growth of trees defoliated 40 percent. Late-season defoliation, however, can be more deleterious than earlier defoliations that allow time for subsequent recovery before bud set in the fall. Location of defoliation on the tree was insignificant to growth loss, indicating that an insect preferring new foliage would do no more damage than one preferring old foliage.

Effects of basal injury by girdling and boring followed a pattern somewhat similar to that of defoliation. Damage had to be severe enough to weaken the stem almost to the point of collapse before there was significant growth loss. Basal injuries healed rapidly in vigorous stock and caused no lasting effects. We should point out that such wounds, however, may be infection sites for pathogens that could kill the trees.

We should also note that these tests did not encompass direct damage to leaders. Several modes of insect attack result in leader damage, and these are difficult to simulate mechanically. In particular, the feeding of aphids does not lend itself to investigation by simulation. Experiments with caged insects are needed in this regard.

DISCUSSION

Since research has begun on Populus pests in the North Central Region, the cottonwood leaf beetle has been the predominant defoliator with the greatest impact. Because we now know a great deal about the behavior of this insect as well as much about the physical factors of the host trees, the next appropriate step for research is to examine the chemical cues in Populus that repel or attract and safeguard the insect once on the tree. Research will need to interrelate the physical and chemical factors in order to understand host resistence mechanisms. For instance, we will need to learn what concentrations of nitrogen and other nutritional

components of the foliage relate to the feeding behavior and growth of the cottonwood leaf beetle. Also, allelopathic chemicals in the host that are certain to provide further mechanisms of host resistence. Populus is ideal for such research because it has a wide range of resistance and susceptibility to this beetle. Because of this and because the cottonwood leaf beetle is the most important defoliator in the region, it might be considered first in pest-resistent breeding programs.

Two insects we investigated--the spotted poplar aphid and the poplar-gall saperda--which are potentially destructive pests of nursery stock and 2- to 3-year old planted trees, caused only minor impact, even when abundant. This suggests that these two insects have been overrated as pests of poplars. For instance, aphid colonies exceeding 800 insects only slightly deformed a few leaves on the tips of some sprouts. Growth differences were insignificant as compared to unattacked sprouts. Similarly, saperda caused a few trees to break over or die-back, but most of those trees resprouted the following year and nearly caught up in height within 2 years. The saperda may have more injury potential under unusual circumstances. High winds or ice storms, for example, might precipitate greater stem breakage. Two or 3 years after outplanting, however, most poplars in our study were nearly immune to stem-injury from saperda.

Septoria canker is the worst disease organism investigated on Populus in both the nursery and plantations. Because many otherwise favorable clones are attacked, this disease will require further and immediate research for its prevention and control.

The poplar-and-willow borer is potentially the worst boring insect so far encountered in the region mainly because it can destroy sapling-size trees. Research will need to continue on this pest in the next few years in order to learn the full extent of its impact. Cultural practices, such as fertilization and thinning, should be tested further to learn how they modify the weevil's behavior.

Cultural practices should also be researched on the tarnished plant bug and Septoria canker, especially where 1-to 2-year old trees need protection. Cover cropping, the role of weeds, and variables related to moisture also need to be studied.

All these studies suggest further that we need to change how we perceive control of some Populus pests--particularly the insects. The poplar-gall saperda and the spotted poplar aphid are two good examples in which damage potential appears to be high but control may rarely be needed. The damage simulation tests further show that Populus can tolerate much defoliation and boring injury before control treatments are needed. Defoliation at 50- to 60-percent levels for 2 or more consecutive years seems to be nearly inconsequential to growth and biomass production. Similarly, borers need to literally riddle a stem before economic thresholds are reached and control is needed.

In conclusion, it appears that if proper pest-preventive measures are taken before and during the growing of Populus hybrids, reasonably resistant trees are planted, and good cultural treatments are adhered to, many Populus pests should be kept at sufficiently low levels to maintain full biomass production.

LITERATURE CITED

Bassman, J., W. Myers, D. Dickmann, and L. Wilson. 1982. Effects of simulated insect damage on early growth of nursery-grown hybrid poplars in northern Wisconsin. Canad. J. For. Res. 12:1-9.

Burkot, T. R. and D. M. Benjamin. 1979. The biology and ecology of the cottonwood leaf beetle, Chrysomela scripta (Coleoptera: Chrysomelidae), on tissue cultured hybrid Aigeiros (Populus x euramericana) subclones in Wisconsin. Canad. Entomol. 111:551-556.

Caldbeck, E. S., H. S. McNabb, Jr. and E. R. Hart. 1978. Poplar clonal preferences of the cottonwood leaf beetle. J. Econ. Entomol. 71:518-520.

Harrell, M. O., D. M. Benjamin, J. G. Berbee, and T. R. Burkot. 1981. Evaluation of adult cottonwood leaf beetle, Chrysomela scripta (Coleoptera: Chrysomelidae), feeding preference for hybrid poplars. Great Lakes Entomol. 14:181-184.

Harrell, M. O., D. M. Benjamin, J. G. Berbee, and T. R. Burkot. 1982. Consumption and utilization of leaf tissue of tissue-cultured Populus x euramericana by the cottonwood leaf beetle, Chrysomela scripta (Coleoptera: Chrysomelidae). Canad. Entomol. 114:743-749.

Moore, L. M., L. F. Wilson, and M. E. Ostry. 1982a. Poplar-and-willow borer injury in two hybrid poplar clones. In: Zavitkovski, J.: Hansen, E. A., eds. Proceedings, North American Poplar Council, 19th Annual Meeting; 1982 July 20-22; Rhinelander, WI. Manhattan, KS: Kansas State University Press; 1982: 59-62.

Moore, L. M., M. E. Ostry, L. F. Wilson, M. J. Morin, H. S. McNabb, Jr. 1982b. Impact of Septoria canker, caused by S. musiva on nursery stock and first-year plantation coppice. In: Zavitkovski, J.; Hansen, E. A., eds. Proceedings, North American Poplar Council,

19th Annual Meeting, 1982 July 20-22; Rhinelander, WI. Manhattan, KS: Kansas State University Press; 1982: 44-50.

Morris, R. C. 1980. The poplar-and-willow borer of hybrid poplars in Ontario, Cryptorhynchus lapathi. Ontario Ministry of Nat. Res. For. Res. Branch, Pest Cont. Sec., Pest Cont. Report No. 12, 8 p.

Sapio, F. J., L. F. Wilson, and M. E. Ostry. 1982. A split-stem lesion on young hybrid Populus trees caused by the tarnished plant bug, Lygus lineolaris (Hemiptera [Heteroptera] Meridae). Great Lakes Entomol. 15:237-246.

Waterman, A. M. 1954. Septoria canker of poplars in the United States. U.S. Dept. Agric. Circ. 947. 24 p.

Wilson, L. F. 1979. Insect pests of poplars in the Lake States. In: Proceedings, North American Poplar Council, 16th Annual Meeting, 1979 Aug. 14-17; Thompsonville, MI. p. 75-81.

DISEASES OF INTENSIVELY CULTURED HYBRID POPLARS: A SUMMARY OF RECENT RESEARCH IN THE NORTH CENTRAL REGION

M. E. Ostry, Associate Plant Pathologist, NCFES, St. Paul

H. S. McNabb, Jr., Professor, ISU, Ames[1/]

Abstract.--Several potentially damaging diseases of hybrid poplars have been identified in the north-central United States. Among the most serious are leaf and stem diseases caused by Melampsora, Marssonina, and Septoria. Short-term chemical controls are of limited usefulness. The most practical control strategy appears to be the use of resistant clones obtained through local screening, combined with various cultural measures, and integrated into overall management plans.

Introduction

The increasing demand for economical wood fiber and energy, together with the competition for land has created an interest in establishing short-rotation, intensive tree culture systems to maximize biomass yield per unit area. Recent research in the north-central United States has concentrated on the use of hybrid Populus and the application of agronomic practices to establish and manage high yielding plantations on short rotations to provide raw material for industrial and energy uses. Populus appears well-suited for management under such a system because of its rapid growth, genetic diversity, ease of vegetative propagation, and coppice regeneration. However, past experience with growing hybrid poplars in Europe, Canada, and the southern and northeastern United States indicates that pathogens and insect pests can severely limit the productivity or lower the quality of affected trees. Because plantations are costly to establish and maintain, they must be protected from serious damaging agents. This paper will summarize the major findings of recent research into the potential impact and control of diseases of intensively cultured hybrid poplars in the north-central region.

[1/] Journal Paper No. J-10900 of the Iowa Agriculture and Home Economics Experiment Station Ames Ia. 50011 USA, Project No. 2524

Disease Detection and Pathogen Identification

Foliage Diseases

Poplar leaf rust, caused by Melampsora medusae, was the first disease recognized as having the potential to severely reduce biomass yields (Schipper and Dawson 1974). Rust reduced wood volume of susceptible clones up to 42 percent in research plots in Wisconsin, Minnesota, and Iowa (Widin and Schipper 1981). Impact from rust is most severe on poplars planted within the natural range of Larix, its alternate host, where poplars are infected early in the growing season. Other virulent races of M. medusae may also be present (Singh and Heather 1982). In addition, other rust species could infect previously resistant poplars. Fungicides will protect trees, but screening and selecting rust-resistant clones is the best control strategy.

Insects and pathogens affecting 32 clones of hybrid poplars were detected and identified in 13 small plantations planted throughout the north-central region in 1976 and 1977 (Ostry 1979). Data were collected on the prevalence and severity of damaging agents several times during each growing season through 1982.

Several foliage diseases, some of them potentially serious, were identified. Poplar leaf rust was of lesser importance in the southern plantations than in the north where premature defoliation of susceptible clones was common. Phyllosticta leaf spot, a

disease of minor importance except on young trees, was most severe in southern Illinois and rarely found north of Iowa. Septotinia podophyllina was found only in the northern region. It causes a leaf spot in the lower crown late in the season but may be of periodic importance on young trees. Venturia macularis causes a leaf and shoot blight that kills terminal portions of trees, reduces growth, and deforms trees. It was most severe on young trees in the northern region.

Marssonina brunnea causes a leaf spot and lesions on the current year's stem growth and was present throughout the region. Highly susceptible P. X euramericana clones were prematurely defoliated by Marssonina, resulting in reduced growth. Other reductions in root growth and depletion of root starches may predispose defoliated trees to environmental stresses and other diseases (Bassman and Dickmann 1982).

Marssonina was of minor importance until it reached epidemic proportions at Rhinelander, Wisconsin, in 1978 and at Rosemount, Minnesota, in 1980, illustrating how disease impact can change in poplars when inoculum levels increase and conditions for spore dispersal and infection of susceptible clones exist. Marssonina infection decreased in 1981 at Rosemount largely because most of the susceptible trees were more than 8 m tall and their lower live crowns were 3-4 m above the ground. Moisture dries more quickly on leaves at this height, reducing conditions favorable for infection. From observations in our research plots, it appears that Marssonina is most damaging on young trees grown at close spacings.

To better understand the life history of Marssonina and other pathogens, we placed spore traps in and around poplar plantations in Michigan, Wisconsin, Minnesota, and Iowa from 1980-1982. Weather data also were collected. Disease symptoms and tree phenology were recorded throughout the growing season. We found that Marssonina conidia or ascospores of its perfect state (Drepanopeziza) are liberated throughout the entire season (Figure 1).

In 1977 leaf spot caused by Septoria musiva was found on poplars in all plantations except Rhinelander, where it was not found until 1980. It was, however, present on native P. balsamifera in this area. Premature defoliation of trees of several highly susceptible clones reduced their growth and predisposed them to other pathogens and environmental stresses, resulting in extensive dieback. Infection of poplar leaves in spring results from ascospores of Mycospharella populorum, the perfect state of S. musiva, being liberated from infected leaf debris on the ground (Figure 1).

Stem diseases

Deer browsed heavily on trees in northern Minnesota and Michigan. Diseases such as Venturia and heavy weed competition prevented many trees from outgrowing the reach of deer and Cytospora dieback was common on these trees. Vigorously growing trees in larger plantations could outgrow the deer hazard.

Branch and stem diseases other than Cytospora were rare on trees until after 1978, when cankers caused by Dothichiza populea and S. musiva became important. Cankers caused by Dothichiza were most severe at Rosemount. Stem breakage at these cankers began in 1981. Susceptibility varied by clone and species perhaps because of the difference in clonal rooting depth (Haywood and McNabb 1979). The perfect state of Dothichiza, Cryptodiaporthe populea, was present on infected trees--the first report of the perfect state in the United States. The ascospores of this perfect state may be important in the spread of the fungus within plantations. Field testing to select trees for drought resistance may be warranted to reduce the incidence of this disease as well as Cytospora and Phomopsis dieback. To guard against stress related diseases, clones should be matched to sites they will occupy.

Septoria cankers were first recorded in 1978 near Ames, Iowa, and at Rosemount. Poplar stems inoculated in a greenhouse with isolates of Septoria obtained from leaf spots resulted in the typical sunken cankers observed in the field. Canker severity remained high at these two locations, and stem breakage began in 1979 as a result of multiple cankers on stems of highly susceptible clones. Many of these trees have resprouted and died back repeatedly from subsequent cankering. In contrast, trees of these same clones growing at Rhinelander remained healthy until late summer, 1981, when Septoria canker was first observed. Cultivation was more frequent and thorough at Rhinelander than at other study sites and may have been a factor in reducing overwintering inoculum. Cultivation was discontinued when tree size made it difficult to operate machinery in the plantings and spore trapping confirmed an increase in inoculum within plantings.

Susceptibility to Septoria varies, necessitating local screening of poplar clones before large acreages are planted. In

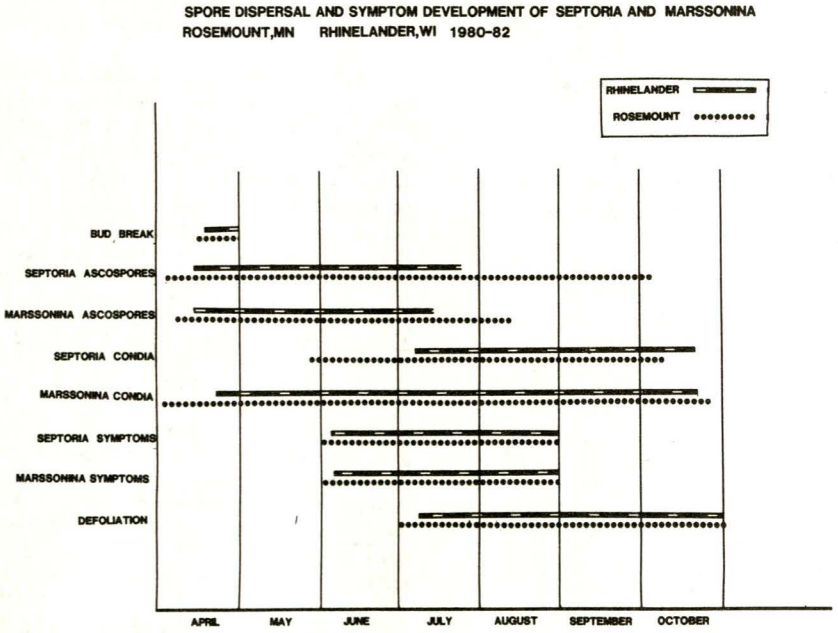


Figure 1.--Spore dispersal and symptom development of Septoria and Marssonina at Rosemount, Minnesota and Rhinelander, Wisconsin 1980 - 1982.

one area where this was not done, trees of many susceptible clones were propagated in a nursery and outplanted. Heavy cankering by Septoria resulted in early failure of several plantations and many clones were removed from the nursery (Moore et al. 1982).

Root Diseases

Armillariella mellea causes a root and butt rot usually, but not always, of weakened trees. A late spring frost in 1981 at Rhinelander killed flushed leaves and cambium of trees of several clones that were also highly susceptible to foliage disease. A. mellea was found on these trees and together with other pathogens resulted in the decline and eventual death of the trees. Root rots may become increasingly important in older plantations and stands of coppice regeneration.

Screening for Resistance

Three plantations, each containing more than 500 species and clones of poplars were planted in 1978 to screen many genotypes for field resistance to Melampsora, Marssonina, and Septoria. Plantations were located at Rosemount, Rhinelander, and near Ames. Resistance to the diseases caused by the major pathogens varied widely. As in the previously described plantings, identical clones planted at Rosemount and near Ames were heavily infected by Septoria, but those clones were free from cankers until 1981 at Rhinelander. Cultivation again was much more thorough at Rhinelander than at the other sites and is thought to be responsible for less Septoria infection. Melampsora defoliated highly susceptible clones at Rhinelander more than a month before symptoms appeared on the same clones at Ames. Tree growth and winter hardiness also varied by clone and location. At this time, 104 of the clones planted are disease resistant at all 3 locations. A total of 130 clones are too susceptible to Septoria canker to be recommended for planting at any of the locations (Ostry, unpublished data).

Results of this screening study revealed the importance of field testing clones for disease resistance. Repeated observations of disease development over the growing season detected clones that became heavily infected with rust or Marssonina late in the season in contrast to highly susceptible clones that became infected early in the season. Some clones moderately susceptible to Melampsora at Rhinelander could be safely planted near Ames. Genotype-environmental interactions and variation among clones in susceptibility to diseases underscore the importance of "tailoring" planting stock for each site and area within the region. In the future it may be desirable to screen clones at the spacing at which they will be grown, to judge their relative competitiveness and disease susceptibility at that spacing (McNabb et al. 1982a).

Impact of Septoria Canker

Impact of Septoria canker on a mixed hybrid poplar plantation planted at 10,000 trees/ha was studied in central Iowa from 1977 through 1981. Biomass production of the first rotation was determined from a cut made in the winter, 1979-80. The mixture included clones with high and moderate susceptibilty as well as resistant hybrids of similar biomass production potentials (Table 1). The resistant hybrid produced three times more biomass by weight than did the highly susceptible clone. In addition, 30 percent of the resulting stumps failed to resprout in the highly susceptible hybrid compared to only 3 percent failure for each of the other 3 clones (McNabb et al. 1982b). In pulping studies, cankered wood, either as the sole source or in mixtures with healthy wood where it exceeded 25 percent by dry weight, proved unsatisfactory for pulp fiber used in kraft paper production (Holt et al. 1981). Cankered wood had higher lignin and extractive content than uncankered wood. Paper produced from this pulp stretched significantly further, and it had lower tensile and bursting strength, burst factor, and breaking length.

Chemical and Cultural Control Trials

Short-term chemical disease control is needed, especially in propagation nurseries, to ensure that only healthy stock is produced and used in establishing plantations. Fungicides also may be appropriate to reduce inoculum in plantations, but long-term controls using cultural treatments in addition to resistant clones are more desirable.

The Central Iowa plantation used to assess impact of Septoria also was used to test the effectiveness of three fungicides for managing S. musiva. During the first rotation an early and midseason spray of captafol, as well as bimonthly sprays, controlled Septoria canker near the level of the resistant clone (Table 1) (McNabb et al. 1981).

Septoria canker is a serious problem in nursery cutting beds and coppiced stands

Table 1. Results of *Septoria* canker control trials

Clone No. [a]	Ames, IA (plantation) Captafol spray			Freesoil, MI (nursery) Benomyl spray			
	Unsprayed check	early & midseason	bimonthly	Unsprayed check	early season	bimonthly	cultivation
	Canker rating [b]			Canker index [c]			
NE 1	5.1	0.9	0.8	.46	.00	.00	.45
NE 299	3.6	0.9	0.6				
NE 298				.00	.00	.00	.07
NE 387	2.9	0.6	0.5	.15	.06	.00	.10
NE 19	0.3	0.0	0.2	.00	.00	.00	.00

[a] NE 1 = *Populus nigra* L. X *P. laurifolia* Ledeb. 'Strathglass' (highly susceptible)

NE 299 & NE 298 = *P. nigra* var. *betulifolia* Torr. X. *P. trichocarpa* Torr. and Gray (moderately susceptible)

NE 387 = *P. candicans* Ait. X *P.* X *berolinensis* Dippel (moderately susceptible)

NE 19 = *P. nigra* cv. *charkowiensis* X *P. nigra* var. *caudina* Tenore (resistant)

[b] Canker Rating = 0 - no cankers; 0.1-9.9 - increasing numbers of branch and stem cankers; 10-tree breakage and death

[c] Canker Index = Number of infected stumps/number planted

(Moore et al. 1982, McNabb et al. 1982b). Chemical control of this disease was tested in Minnesota in 1980 and 1981. Trees were cut yearly to simulate a nursery cutting bed. Four fungicides and four spray schedules including check plots were randomized within the plots. Benomyl applied monthly or bimonthly at 1 lb. active ingredient per 100 gallons of water resulted in less cankering than any of the other treatments.

On the basis of these preliminary results, we began a control study in 1981 at the poplar nursery of the Packaging Corporation of America near Manistee, Michigan. The objective of this study was to compare clone resistance, and chemical and cultural controls to disease incidence. A 30x300-foot length of a nursery bed was planted with four clones variously susceptible to Septoria (Table 1). Four treatments were randomly assigned among the plots except for the plots designated to be cultivated. These plots were on one end of the nursery bed to facilitate use of nursery equipment. Plots were cultivated as soon as the ground was workable in the spring through the end of May. Benomyl was sprayed on some of the remaining plots either once at the beginning of the season or bimonthly throughout the season; other plots were left unsprayed as checks. Disease data were recorded from the center trees of each plot and the other trees served as buffers between treatments.

No significant results were obtained at the end of 1981 because leaf disease was light on all plots and no cankers were present. All plots were harvested along with the production nursery beds in early winter.

The same treatments were applied in 1982 and data were recorded in September. Leaf disease was greater than in 1981 and stem cankers were present. Previous experience had shown us that Septoria canker prevalence increases as inoculum on fallen infected leaves increases. In addition, greater infection in 1982 also was caused by increased density of stems resulting from multiple sprouts on each stump. Both chemical spray schedules were effective in reducing cankering of susceptible clones (Table 1). Cultivation, however, failed to reduce disease. Clones previously known to be resistant or only moderately susceptible were either healthy or lightly infected.

Spore trapping indicated generally low inoculum levels in the nursery. However, the proximity of the cultivated plots to unsprayed susceptible plot trees provided inoculum that may have caused failure of cultivation to reduce disease. Cultural controls may only be effective in reducing disease if done thoroughly and then only if inoculum from outside sources is absent or light.

Benomyl, as was shown earlier with captafol, was effective in preventing disease development in even the most susceptible clone tested. But, the impact that Septoria canker can have in plantations where chemical controls may not be feasible dictates that only resistant clones be planted where this disease is known to be a hazard.

Intensive Culture Versus Disease Development and Management Implications

Silvicultural systems developed for rapid production of wood fiber can favor the development of disease in some instances. Growers must be aware that conditions that maximize tree growth may increase disease incidence or severity so that production gains over natural stands are severely reduced or completely lost.

Populus, as a genus, is host to many insects and pathogens. Many poplar species and hybrids now being planted are not native to our area. Introduction of exotics has resulted in instances where an endemic pathogen in native poplar stands has caused serious disease problems. For example, S. musiva causes minor leaf spotting of native poplars. In contrast, on many hybrids between the sections Aigerios and Tacamahaca, this fungus not only causes premature defoliation of highly susceptible trees, but also causes cankers on stems and branches. Industrial and research plantings examined thus far in Michigan, Wisconsin, Minnesota, and Iowa have revealed that hybrids involving P. trichocarpa, P. laurifolia, and P. maximowiczii are especially susceptible to cankering. Species of Marssonina are periodically important on native poplars. However, M. brunnea causes a serious leaf disease of many P. X euramericana clones. Susceptible clones can be prematurely defoliated and predisposed to other diseases and to winter injury, especially in the northern portion of the north central region.

We only need to look at modern agriculture and the chemical and cultural treatments needed to control diseases to see the potentially serious risk involved in growing trees in a monoculture at close spacings. Use of clones means that all trees of a susceptible clone can be affected in a disease outbreak. Dense plantings create many conditions that can increase disease

severity (Schipper 1976). Density influences air movement, leaf wetness, and humidity within a plantation--important factors in the infection and development of pathogens (McNabb et al. 1982a). Proximity of trees to each other within a plantation influences rate of spread of pathogens and subsequent development and severity of diseases. Even-age management similarly can increase disease severity because all trees may be equally susceptible to a particular disease at their stage of development.

In the vegetative propagation of poplars, serious disease agents may be moved along with cutting or rooted stock. Viruses, detected in many poplar clones being used, threaten vegetatively propagated poplar monocultures, and steps should be taken to eliminate them from planting stock (Berbee et al. 1976, Van der Meer et al. 1980). We have found that unrooted hardwood cuttings taken from clonal nurseries in the Lake States can be infected with Septoria, Marssonina, and Dothichiza. These serious pathogens can be moved to areas of previously uninfected trees. Fungi that are weakly parasitic on poplars such as Cytospora and Phomopsis can weaken improperly stored cuttings so that they produce plants susceptible to other stresses (Ostry and McNabb 1982).

Cultural treatments such as plowing, discing, and irrigation also can influence disease development. Thin-barked poplars can be easily wounded by implements, creating entrances for canker and decay fungi. Plowing may kill or reduce soil microbiota such as saprophytic fungi that would otherwise limit soil-borne pathogen populations. Irrigation, especially overhead systems, may increase foliage diseases because of possible increased spore dispersal and infection resulting from longer periods of leaf wetness.

Poplars growing in an agroecosystem are subject to conditions much different from those in a natural, dynamic ecosystem. Intensive culture systems can create an imbalance, resulting in rapid development and multiplication of pathogens. We are growing a susceptible host on which several potentially damaging pathogens are present. Manipulating the environment around these trees can be extremely important because the environment is a controlling influence on pathogens as well as on the host. Vigorous trees can generally tolerate greater incidence of pathogens and insect pests. Tree vigor, disease incidence, and pathogen and insect populations must be monitored under the various cultural systems used to guard against an imbalance that may cause an insect or disease problem to develop.

Summary and Conclusions

Many pathogens of hybrid poplars have been identified in the north-central region. Some have no apparent impact on tree growth or quality. Other pathogens may be of periodic importance. These need to be monitored so that control actions, either in the current rotation or the next, can be taken to minimize damage. Diseases can increase to unacceptable levels in the event of a change in the host, environment or pathogen. A few pathogens are, however, usually destructive to susceptible trees, reducing tree growth, quality and survival. The risks associated with these pathogens must be considered in any planting plans. Of importance is management's objective in growing the trees: what will be the use of the wood produced?; are quantity, quality, or both important?; how long will the trees be grown?; will the stand be coppiced? These are important questions to consider in terms of diseases impact and disease control. Some of the fastest growing trees we have studied are also the most susceptible to one or more diseases. These diseases pose some threat to trees grown on short rotations, but they may cause serious problems for trees grown on longer rotations. Septoria, for example, may or may not adversely affect management's objectives. Defoliation and growth loss from the disease are severe on only the most susceptible clones, and cankering of plantation trees usually is serious 3-4 years after planting. Therefore, susceptible clones can be grown on mini rotations, but not in shelterbelts or on longer rotations. Wood fiber quality of cankered trees is satisfactory for fuelwood or lower quality paper, but not for high-quality paper. Septoria infection is much more severe in coppiced stands so coppicing highly susceptible clones is highly risky.

Proper planning before planting, including selection of clones with resistance to important diseases, and good management aimed at maintaining high tree vigor will avoid many future problems. Integrating disease control into silvicultural practices is the most promising strategy. Higher economic returns from intensively managed hybrid poplar plantations in the future will justify disease and insect control and give managers more flexibility in dealing with pest problems.

Acknowledgement

We thank Robert Resendez of the North Central Forest Experiment Station and Rita S. Sonnelitter and Peter E. Gerstenberger, graduate students of Iowa State University, for their assistance.

Literature Cited

Bassman, John H.; Dickmann, Donald I. Effects of defoliation in the developing leaf zone on young Populus X euramericana plants. I. Photosynthetic physiology, growth, and dry weight partitioning. Forest Sci. 28(3): 599-612; 1982.

Berbee, J. G.; Omuemu, J. O.; Martin, R. R.; Castello, J. D. Detection and elimination of viruses in poplars. Gen. Tech. Rep. NC-21. St. Paul, MN: U.S. Department of Agriculture, Forest Service, North Central Forest Experiment Station; 1976: 85-91.

Haywood, William F.; McNabb, Harold S., Jr. Moisture stress and incidence of stem cankers in intensively grown poplars. In: Proceedings of the first north central tree improvement conference; 1979 August 21-23; Madison, WI. 1979: 123-132.

Holt, K. E.; McNabb, H. S. Jr.; Rothlauf, M. A.; Manwiller, F. G. Ostry, M. E. Characteristics of Kraft paper made from Septoria cankered Populus grown under short-rotation, intensive culture (Abstr.). Phytopathol. 71: 226; 1981.

McNabb, H. S. Jr.; Ostry, M. E.; Tipton, P. A.; Sonnelitter, R. S.; Zito, J. M.; Caldbeck, E. S. Fungicidal management of Septoria canker of Populus grown under short-rotation, intensive culture (Abstr.) Phytopathol. 71: 242, 1981.

McNabb, Harold S., Jr.; Hall, Richard B.; Ostry, Michael E. Biological and physical modifications of the environment and the resulting effect upon the host-parasite interactions in short-rotation tree crops. In: Heybroek, H. M.; Stephan, B. R.; von Weissenberg, K., eds. Proceedings, Third International Workshop on the Genetics of Host-parasite Interactions in Forestry: Resistance to Diseases and Pests in Forest Trees; 1980 September 14-21; Wangeningen, the Netherlands. Wangeningen, the Netherlands: Centre for Agricultural Publishing and Documentation (Pudoc); 1982a: 60-71.

McNabb, H. S., Jr.; Ostry, M. E.; Sonnelitter, R. S.; Gerstenberger, P. E. The effect and possible integrated management of Septoria musiva in intensive, short-rotation culture of Populus in the north central states. In: Zavitkovski, Jerry; Hansen, Edward A., eds. Proceedings, North American Poplar Council Meeting; 1982 July 20-22; Rhinelander, WI. Manhattan, KS: Kansas State University; 1982b: 51-58.

Meer, F. A. van der; Maat, D. Z.; Vink, J. Poplar mosaic virus: purification, antiserum preparation, and detection in poplars with the enzyme-linked immunosorbent assay (ELISA) and infectivity tests on Nicotiana megalosiphon Neth. J. Pl. Path. 86: 99-110; 1980.

Moore, Lincoln M.; Ostry, Michael E.; Wilson, Louis F.; Morin, Michael J.; McNabb, Harold S., Jr. Impact of Septoria canker, caused by S. musiva on nursery stock and first-year plantation coppice. In: Zavitkovski, Jerry; Hansen, Edward A., eds. Proceedings, North American Poplar Council Meeting; 1982 July 20-22; Rhinelander, WI. Manhattan, KS: Kansas State University; 1982: 44-50.

Ostry, Michael E. Disease research of poplars grown under intensive culture in the north central region of the United States. In: Proceedings, 16th Annual Meeting, North American Poplar Council; 1979 August 14-17; Thompsonville, MI.; 1979: 83-91.

Ostry, M. E.; McNabb, H. S., Jr. Preventing blackstem damage to Populus hardwood cuttings. In: Zavitkovski, Jerry; Hansen, Edward A., eds. Proceedings, North American Poplar Council Meeting; 1982 July 20-22; Rhinelander, WI. Manhattan, KS: Kansas State University; 1982: 36-43.

Schipper, A. L., Jr.; Dawson, David. Poplar leaf rust -- A problem in maximum wood fiber production. Plant Dis. Rept. 58(8): 721-723; 1974.

Schipper, A. L., Jr. Poplar plantation density influences foliage diseases. Gen. Tech. Rep. NC-21. St. Paul, MN: U.S. Department of Agriculture, Forest Service, North Central Forest Experiment Station; 1976: 81-84.

Singh, S. J.; Heather, W. A. Temperature sensitivity of qualitative race-cultivar interactions in Melampsora medusae Thum. and Populus species. Eur. J. For. Path. 12: 123-127; 1982.

Widin, K. D.; Schipper, A. L., Jr. Effect of Melampsora medusae leaf rust infection on yield of hybrid poplars in the north-central United States. Eur. J. For. Path. 11(7): 438-448; 1981.

SOME IMPLICATIONS OF *POPULUS* INTENSIVE CULTURE ON NONGAME BIRDS

Richard L. Verch[1/]

Abstract.--Intensive culture of *Populus* will affect nongame bird habitat. Conversion of old fields to *Populus* plantations will destroy habitat favorable to certain species and produce habitat that will attract different species. Effects of this conversion can be lessened by planting plantations with irregular shapes and by leaving patches (.4 hectares) of existing vegetation when plantation size exceeds 60 hectares.

INTRODUCTION

Demand for wood and wood products has increased rapidly in recent years. More and more of the traditional "wild" land is beginning to serve a multitude of needs to our complex society. Management of land for aesthetic purposes, game habitat, camping, snowmobiling, skiing, and water and soil conservation all have potential conflicts with efficient growing and harvesting of timber. According to Davis (1979) competing uses for land have been and will continue to be one of the most important influences on the survival of America's wildlife resources. To partially meet the increasing demand for wood, a silvicultural system called short-rotation intensive culture (SRIC) is being explored. Large plantations of intensive cultured poplars (*Populus* spp.) planted by paper companies and other private land owners may have important effects on nongame birds.

INTENSIVE CULTURE CHARACTERISTICS

Intensive culture techniques for trees are now being explored. One method is similar, at least initially, to farming traditional row-crops. Existing vegetation is removed and the site is sprayed with a non-selective herbicide, plowed and disked the fall before planting. In the spring, the field is redisked and a pre-emergent herbicide such as linuron is applied just prior to planting unrooted cuttings.

Nitrogen fertilizer is applied annually at a rate of up to 170 kilograms per hectare in a split application (June and July). The plantations are irrigated to maintain a soil moisture tension below -0.5 bars. Insecticides may be used to control serious insect outbreaks if necessary.[2/]

Optimum spacing for the trees appears to be between 1X1 and 2X2 meters. Such spacings provide for complete canopy closure during the second year so that competing vegetation will be shaded out. In trial plantations established at Rhinelander, Wisconsin, herbaceous vegetation is almost completely suppressed due to shading by the third year.[3/]

Tree growth is rapid with heights reaching 3.6 meters after two growing seasons and over 9 meters after 5 years. Estimated rotation time of plantations varies from

[1/]Professor of Biology, Northland College Ashland, Wisconsin 54806.

[2/]E. Hansen, Forestry Sciences Laboratory, Rhinelander, Wisconsin 54501.

[3/]E. Hansen.

8 to 15 years depending upon spacing and desired tree size. After harvesting, the stumps will be allowed to coppice (sprout). Regrowth is very rapid and by the end of the first year, lack of light should prevent herbaceous vegetation from growing beneath the trees.

An alternate site preparation technique, the no-till method, is being tried by Packaging Corporation of America (PCA). In this procedure only chemicals are used to control weeds and to prepare the site for planting. Fields are sprayed with a non-selective herbicide the year prior to planting. Planting material consists of rooted stock, 1.3 cm in diameter X 38 cm tall. Once the trees are planted and prior to any germination of annual weeds a herbicide is applied.[4/] Additional herbicide treatments may be required in June and again in late July to control weeds. Spacing at PCA is about 3X3½ meters for a planting goal of 625-900 trees per hectare. In this method, it may take up to 7 years to eliminate herbaceous vegetation.

Plantations of fast growing poplars will likely have characteristics that will have major effects on birds, both those within the plantation and those found in adjacent areas. The impact of these plantations will be due primarily to site preparation to establish the original plantations and physical structure of the established plantations.

ESTABLISHMENT OF ORIGINAL PLANTATIONS

Economics dictate the areas that will be planted to SRIC. Abandoned pastures and fields are likely sites for plantations. Site conversion of low producing or non-producing woodlots to more economically profitable plantations may also take place. Morin indicates that at the present time idle land is plentiful but very expensive.[5/] This determines, to a large extent, the number of acres that industrial users will purchase and plant. Morin also mentioned that private landowners may be interested in fast growing poplars as trees for shelter belts and as a source of firewood for home heating. However, land that is suitable for good northern hardwoods is not likely to be converted to fast growing poplars. Practically, the sites that are best sites for SRIC are also the best sites for other uses (farming, hardwood production or natural regeneration).

4/M. Morin, Packaging Corporation of America, Manistee, Michigan 49854.

5/M. Morin

Field studies on the environmental effects of intensively cultured tree plantations are just beginning. Curtis (1978) indicates a need for research that could provide indices of quantitative avian use of forest habitats under various management systems.

Initial effects during the conversion of fields and forest openings to Populus plantations will have a distinct impact on the existing habitat. Wood and Niles (1978) indicate intensive culture site preparation for planting essentially eliminates all bird habitat for a period of time. Bird activity that does exist on a newly planted site generally will be restricted to feeding on worms and insects that are exposed by the tilling of the soil. During the early growing seasons some avian species requiring early successional stages may benefit. Fields prepared by the no-till method will still have dead vegetation on them in which some species may forage and nest. In addition the dead vegetation provides cover for small rodents which in turn may be preyed upon by various raptors. Use of available niches during succession of plantations may have an overall favorable effect on the number of birds and species in the area.

Both methods of site preparation completely change the existing habitat. This is of particular concern for birds of Wisconsin fields (Table 1) that are in the 1980 Blue List (Arbib 1979). The Blue List is a list, compiled by the editors of American Birds, of species recently or currently giving indications of non-cyclic population declines or range contractions.

Table 1.--Blue listed birds (1980) of Wisconsin fields.

Northern Harrier	Circus cyaneus
Upland Sandpiper	Bartramia longicauda
Short-Eared Owl	Asio flammeus
Sharp-Tailed Grouse	Pedioecetes phasianellus
Eastern Meadowlark	Sturnella magna
Dickcissel	Spiza americana
Vesper Sparrow	Pooecetes gramineus
Grasshopper Sparrow	Ammodramus savannarum

A second consideration becomes apparent if plantations should be established in upland forest openings. Taylor and Taylor (1979) point to the controversy that exists concerning forest openings: to timber managers they represent non-producing land; to wildlife managers they represent a unique vegetative association of the forest.

The importance of woodland openings to bird life has been discussed by Lay (1938). Avian diversity varies in forest openings. Size of the opening and the surrounding vegetation (type and size) have an important influence on the animal species present (Bond 1957). Taylor and Taylor (1979) report that vegetation species composition of openings seems to be less important than the overall structure of the vegetation. Bird populations have been observed to increase while physical size of the opening was reduced (Evans 1978). The population increase appears to have been the result of the development of more suitable nesting sites as the field passed through successional stages.

If forest openings are converted to SRIC sites or if large openings are interspersed with plantations the type and amount of edge will change. Edges have been considered especially productive areas for many species of birds. Lay (1938) found margins of clearings to contain 41% more species and 95% more individual birds than do the corresponding woodland interiors. Lay indicated that the edge effect usually extends less than 93 meters into the interior of the woodland.

PHYSICAL STRUCTURE OF PLANTATIONS

SRIC plantations will be even aged monocultures with little or no understory, herbaceous vegetation, fallen or dead trees and snags. All these characteristics reduce bird diversity and numbers. Wood and Niles (1978) indicate that simple plant communities such as an even aged monoculture will not support as large a number of bird species as a more heterogenous community. Habitat and niches which allow diversity are simply not present.

Moss (1978) compared three areas showing increasing structural diversity. His conclusions were that maximum density of song birds depends on diverse structured woody vegetation with a good understory. He found four bird species in spruce (Picea) plantations that lacked an understory, eight bird species in more open spruce plantations and fifteen to eighteen species on multi-structured mixed wood plots. Moss (1978) reported that von Haartman found that the two most important factors to influence song bird diversity are vegetation structure (particularly the presence or absence of an understory) and tree species.[6/] Probst (1979) has indicated that tree species composition of eastern deciduous forests has little effect on bird communities because most birds select habitats by vegetation structure. He does mention that smooth barked tree species (some Populus) may contain fewer arthropods than those with rough bark. This could limit bark foragers on some plantations.

Wesley et al (1976) compared bird populations in three areas in Mississippi. One area was a natural riverfront hardwood stand characterized by pecan (Carya illinoensis), green ash (Fraxinus pennsylvanica), box elder (Acer negundo) and sugar berry (Celtis laevigota). The second area was a thinned cottonwood plantation (every other row of trees removed from plantations with 3X3 or 3.6X3.6 meter spacings) and the third area was an unthinned cottonwood plantation with tree spacings again 3X3 or 3.6X3.6 meters. Both the thinned and unthinned plantations had high understory biomass. Songbird numbers were significantly less in the unthinned plantation than they were in the thinned plantation or the natural stand. Preliminary studies showed plantations to be favored by certain species and avoided by others. Wesley et al. (1976) cautioned that while their data indicate a general preference for the natural riverfront hardwood stands it does not necessarily follow that cottonwood plantations are detrimental to songbirds. While plantations remove one type of habitat prized by some species, it may provide food, cover and nesting sites vital to other species.

Temple et al. (1979), while not dealing specifically with plantations, details some disadvantages of even aged forest management that apply to intensive culture. He indicates that vertical diversity is reduced with a concomitant reduction in the number of foraging opportunities available to birds. He also discusses the effects of reducing or eliminating dead or diseased trees from an area. The loss of insects and cavities affects a number of birds particularly members of the winter bird community which feed on insects in bark or wood.

Traditional long rotation forestry that removes small stands of timber through selective logging or clearcutting has a major impact on the avian community (Anderson 1979). Overall the removal of timber attracts edge species and provides a temporary mixture of both forest specialists and edge generalists. Conner and Adkisson (1975) in studies in Virginia found breeding bird diversity to be lowest in a one year old clearcut (mixed oak forest) and highest in a seven year old clearcut. They also noted that forest dwelling birds first appeared in a twelve year old clearcut. The

---

6/ L. von Haartman, "Population Dynamics," Avian Biology 1, D.S. Farner and J.R. King (eds.), London, Academic Press, 1971, pp. 392-459.

short rotation periods (eight to fifteen years) on the Populus plantations may have similar effects.

Disturbance of woodlands adjacent to SRIC plantations may also occur. Robbins (1979) clearly documents the effects of forest fragmentation on certain species of birds. When plantations are interspersed in isolated plots, harvesting of trees will impact the areas where cutting is taking place as well as in the areas where access trails are located.

Practices are possible that could enhance plantations to certain species of birds. "Island refuges" of existing trees and scrub about 0.4 hectares in size could be left in various places in large plantations (60 hectares +). Williamson (1970) indicates that the diversified habitat provided will enrich bird life, even in extensive new forests. Connor and Adkisson (1975) found that leaving dead snags, slash and other debris scattered in certain areas of the plantation also benefits bird life.

A second practice that may serve to increase bird diversity is to allow small openings (less than fourteen hectares) to remain in forested areas. Taylor and Taylor (1979) say the present objective is to maintain 1-5% of the forest land in upland openings. These openings should be managed as part of the forest and should furnish particular life forms including grass, and grass-shrubs as well as stumps, snags and hollow logs.

SUMMARY

Intensive culture of Populus will impact bird communitites. At the present time it appears the major impact will be on bird species of old fields and pastures. The conversion of these areas to SRIC will completely change the niches found in each area. The loss of field niches will impact a number of species and is of particular concern for the birds found on the Blue List (Table 1) and other bird species that nest or feed on the grasses and weeds of the field. Other species not found in fields may find conditions in the plantations favorable so that the total effect on number of bird species in an area may not decrease and may actually increase.

It should be noted that effects of monoculture on wildlife are closely related to the size and shape of the plantation. If plantations make up only a small portion of the total defined land area effects on wildlife including songbirds may be beneficial. Conversely if plantations become the dominant land use pattern the wildlife will be adversely affected. If plantations have irregular shapes and provide lengthy edges this will help mitigate the influence of size as will leaving small stands of existing trees and shrubs.

Wesley et al. (1976) indicates that there is a need for continued study in order to answer the questions about cottonwood plantations as wildlife habitat. Present studies should provide data on the use of plantations by each bird species throughout the growth (age) cycle. Use of the plantations, by birds, on a seasonal basis is also a question being investigated.

LITERATURE CITED

Anderson, S.H. 1979. Habitat structure and bird communities. In Workshop Proceedings: Management of North Central and Northeastern Forests for Nongame Birds. USDA. NC-51.

Arbib, R. 1979. The blue list for 1980. American Birds, 33(6): 830-835.

Bond, R.R. 1957. Ecological distribution of breeding birds in the upland forests of Southern Wisconsin. Ecological Monograph, 27: 325-349.

Conner, R.N. and C.S. Adkisson. 1975. Effects of clearcutting on the diversity of breeding birds. J. Forestry, 73(12): 781-785.

Curtis, R.L. Jr. 1978. A representative sample of ongoing and planned nongame bird research in the Southeastern Region United States. In Workshop Proceedings: Management of Southern Forests for Nongame Birds. USDA. SE-14.

Davis, P.B. 1979. Pigeons to blackbirds: an illustration of the relationships between land use and wildlife resources. Jack-Pine Warbler, 57(1): 3-7.

Evans, E.W. 1978. Nesting responses of field sparrows to plant succession on a Michigan field. Condor, 80(1): 34-40.

Lay, D.W. 1938. How valuable are woodland clearings to birdlife? Wilson Bulletin, 50: 254-256.

Moss, D. 1978. Song-bird populations in forestry plantation. Quarterly Journal of Forestry, 72(1): 5-14.

Probst, J.R. 1979. Oak forest bird communities. In Workshop Proceedings: Management of North Central and Northeastern Forests for Nongame Birds. USDA. NC-51.

Robbins, C.B. 1979. Effect of forest fragmentation on bird populations. In Workshop Proceedings: Management of North Central and Northeastern Forests for Nongame Birds. USDA. NC-51.

Taylor, C.M. and W.B. Taylor. 1979. Birds of upland openings. In Workshop Proceedings: Management of North Central and Northeastern Forests for Nongame Birds. USDA. NC-51.

Temple, S.A., M.F. Mossan and B. Ambuel. 1979. The ecology and management of avian communities in mixed hardwood-coniferous forests. In Workshop Proceedings: Management of North Central and Northeastern Forests for Nongame Birds. USDA. NC-51.

SYNOPSIS OF UTILIZATION RESEARCH ON SRIC RAW MATERIALS

John B. Crist [1/]

The take-home message of this paper is this: Raw materials produced using SRIC are suitable for many reconstituted end products. Juvenility, rapid growth, and bark contents do not greatly hinder the usefulness of the raw materials. In the future, increased industrial acceptance of SRIC methods and materials should be a major thrust and is discussed.

The purpose of this review is to see where we have been, where we are now, and where we are going in the future. Initially, the purpose of SRIC (short rotation intensive culture) was to see how productive woody plants could be. How fast could we grow woody plants to satisfy demand for raw materials. Utilization research became important when we realized that SRIC could produce large quantities of biomass, but the biomass was different from that produced by traditional forest management methods. We needed to know if SRIC raw materials were suitable for forest products; which I'll address as the main body of this paper. I'll end the paper with speculation on how to increase industrial acceptance of SRIC methods and materials in the future.

The title of this paper starts with the word synopsis. By definition, a synopsis is a condensed statement. The condensed statement and the take-home message of my paper is this: Raw materials produced using SRIC are suitable for many reconstituted end products. Let's examine the words used in this statement. First, I used the verb "are," not "maybe," because much research has proven acceptable products can be made from them. Next, the word "suitable" was used, not "best," because products can be made that are within industry standards or guidelines, but there are limitations. The word "many" instead of "all" was used because there have been some failures, but mostly successes. Next, "reconstituted" was used to show these materials are best for products other than those made from solid wood. Lastly, "end products" was used instead of "forest products" to show that uses are broader than traditional uses, such as chemicals and animal feed.

The take-home message is a strong statement. But it is not nearly as novel or controversial as it was in 1976 when some of us in the SRIC program theorized the statement was true. At the 1976 review, I presented a paper on utilization advantages of SRIC materials. Most of the speculation in that paper has proven true, and some warrants repeating. At that time, many people thought that juvenile materials were unsuitable for utilization. However, in the interim, research by us in the SRIC program and by others on different raw materials has shown juvenile materials can be quite acceptable. In fact, some of the strongest and loudest opponents have become advocates of juvenile materials.

[1/] Field Representative, Resource Use, USDA, Forest Service, NA-S&PF, Morgantown, WV.

The changing viewpoints on juvenile materials is not surprising when the nature of the material is considered and understood. Juvenile materials have shorter fiber (cells) than older material. Therefore, in papermaking, there is less opportunity for fiber crossings to form interfiber bonds. The strength of interfiber bonds control most paper strengths, not the strength of the fibers themselves. However, the average cell wall thickness of juvenile material is less than older material. These thin cell walls readily collapse into the desired ribbon shape to provide a large surface for bonding, and they are pliable so the fibers can conform to each other to form strong interfiber bonds. Even though there are less bonds due to the short fibers, the bonds present are strong enough that the net result is paper strength properties that are acceptable and within most product standards.

The conformity is also evident in products other than paper. In waferboard, in which particles instead of fibers are used, the conformity allows excellent bonding between particles, and therefore high strengths in the boards produced.

There are additional erroneous conventions other than juvenility about SRIC materials. Rapid growth is sometimes thought to be detrimental. In most conifers, accelerated growth decreases the proportion of summer wood produced, thereby reducing mechanical strength properties. The reduction in mechanical strength affects the suitability for solid wood products. The convention on rapidly grown conifers should not be applied to SRIC in which mainly Populus is grown and which is not intended for solid wood products. Populus is a diffuse porous species and a main effect of accelerated growth is to prolong juvenility.

SRIC materials will be harvested by whole tree methods. They have high bark contents because of the small diameter, branchy stems. Yet, the bark is different and not as detrimental as bark from older stems. The most troublesome cell types in bark increase with increasing age, and the young stems harvested using SRIC have not developed many detrimental bark cells. Further, another problem with conventional whole tree materials is the amount of grit contained in them. The harvesting machines and methods for SRIC materials will greatly decrease grit contents because the materials will not have as much contact with the ground.

To gain increased industrial acceptance of SRIC, corporate decision makers need to be made aware of advantages inherent in both SRIC systems of fiber production and in the SRIC raw materials themselves. SRIC systems and materials must compete with existing, conventional methods and materials. Let's examine the "market leverage" of SRIC systems and materials which might allow penetration into the market held by traditional methods and materials.

For SRIC materials, juvenility, rapid growth, and bark and grit contents were discussed previously. A great advantage of SRIC material is uniformity. SRIC minimizes variability from the three main sources of variation in woody plants; genotype, age, and culture. The uniform raw materials can be processed with conditions closely tailored for them, thereby increasing yields and gaining efficiency. Also, through selection, clones can be grown that are best suited for a particular process and product --- engineering from the growing plant, through the processing plant, to the final product.

For SRIC systems, some of the advantages are self-evident. Transportation costs can be reduced if plantations are located near mills. Harvesting costs can be less. The machinery needed is smaller and less expensive than traditional harvesting machines because the trees in SRIC are smaller and don't vary as much in size.

A major advantage is the insurance value. If a mill has plantations on their own land, they have a readily available fiber supply source and are not as much at the mercy of labor or weather. This guaranteed supply protects their huge capital investment in the mill or plant. Also, because these plantations are grown on good sites, little affected by weather, the millyard needs less inventory and less capital is tied up.

Some of the above advantages of SRIC materials and systems can be quantified and used in economic analyses. Others are harder to quantify, but are still important in decision making processes. We need good information to provide firm numbers for economic analysis. An analysis should address all steps from plantation establishment through to the

final product, to account for tradeoffs and compromises in and between steps. With firm numbers, a final scenario or thought process in a corporate decision maker's mind might go as follows when he is comparing SRIC methods and materials to those of more traditional forest systems:

-My cost of growing the raw materials may be greater with intensive cultivation and fertilization, etc., but because of high growth rates and short rotations I'm getting greater and quicker rates of return, I need less land to grow my raw materials on.

-My harvesting cost will be less, because of the smaller and less expensive machines I need to handle the small trees.

-My transportation cost will be less, because I'll locate my plantations close to my mill.

-My inventory cost will be less, because my plantations are readily available and growing on good land that is operable during most weather conditions. I need less millyard inventory to ensure my plant can continue to operate.

-My processing costs may be greater, because the high bark contents may decrease yields and I'll need additional processing equipment, but the material is uniform and I can be highly efficient in the processing and I can select and grow materials that are suited for my process.

When I add up all these factors, the net result may be a higher balance on the bottom line of the ledger sheet. I'm vertically integrated, and each vertical step serves as insurance to protect my investment in the next step. I'm less dependent on others such as wood suppliers and I'm little affected by weather. All in all, it's not a bad position to be in, and certainly warrants looking into SRIC.

SELECTED REFERENCES

Crist, John B. 1976. Utilization advantages of material produced in maximum fiber yield plantations. In: Intensive Plantation Culture, USDA For. Serv. Gen. Tech. Rep. NC-21, p. 109-111. North Cent. For. Exp. Stn., St. Paul, MN.

Crist, John B. 1980. Anatomical characteristics of nine Populus clones grown under short rotation intensive culture. In: Proc. 34th Annual Meeting For. Prod. Res. Soc., Boston, MA, July 7-10, 1980, p. 6-7 (Abst.)

Crist, John B., and David H. Dawson. 1975. Anatomy and dry weight yields of two Populus clones grown under intensive culture. USDA For. Serv. Res. Pap. NC-113, 6 p. North Cent. For. Exp. Stn., St. Paul, MN.

Crist, John B., David H. Dawson, and JoAnn A. Nelson. 1976. Wood and bark quality of juvenile jack pine and eastern larch grown under intensive culture. In: 1977 TAPPI Forest Biology Wood Chemistry Conf., Madison, Wis., p. 211-216.

Crist, J. B., and D. W. Einspahr. 1979. Kraft pulp and paper properties of whole tree, short rotation intensively cultured jack pine and eastern larch. Proc. 33rd Annual Meeting For. Prod. Res. Soc., San Francisco, Cal., July 1979, p. 5 (Abst.)

Crist, John B., J. G. Isebrands, and N. D. Nelson. 1979. Suitability of intensively grown Populus raw material for industry. Proc. 16th Annual Meeting NA Poplar Council, Thompsonville, Mich., Aug. 14-17, 1979, p. 65-74.

Crist, J. B., J. G. Isebrands, J. D. Sinkey, and W. L. Bohn. 1978. Thermo-mechanical pulping of 3 short-rotation intensively cultured species. Proc. Ann. Meeting For. Prod. Res. Soc., Atlanta, GA., June 29, 1978, p. 21 (Abst.)

Crist, J. B., and B. E. Schlaegel. 1979. Balsam Poplar--An American Wood. USDA For. Serv. FS-259, 4 p.

Dawson, David H., J. G. Isebrands, and John C. Gordon. 1976. Growth, dry weight yields, and specific gravity of 3-year-old Populus grown under intensive culture. USDA For. Serv. Res. Pap. NC-122, 7 p. North Cent. For. Exp. Stn., St. Paul, MN.

Dickson, Richard E. and Philip R. Larson. 1977. Muka from Populus leaves: a high-energy feed supplement for livestock. In: Eighth TAPPI Forest Biology Wood Chemistry Con., p. 95-99, June 20-22, Madison, WI.

Geimer, Robert L. 1976. "Agricultural" poplars as a raw material for structural particleboard. In: Intensive plantation culture--five years research. USDA For. Serv. Gen. Tech. Rep. NC-21, p. 115-117. North Cent. For. Exp. Stn., St. Paul, MN.

Geimer, R. L., and J. B. Crist. 1980. Structural flakeboard from short rotation intensively cultured hybrid poplar clones. For. Prod. J. 30: 42-48.

Hutchinson, Jay G. 1981. Fast-growing young poplars make good panels, study says. For. Ind. 108(4): 58-59.

Isebrands, J. G. 1977. Short rotation silviculture as an energy source. Proc. Nat. Conf. For. Prod. Util. Res., Madison, Wis. Oct. 25-27, 1977, p. 18 (Abst.)

Isebrands, J. G. 1981. Reaction wood anatomy and its effect on kraft paper from short rotation intensively cultured trees. (Abst.) IAWA Bulletin 2(2&3): 57-58.

Isebrands, J. G., D. W. Einspahr, J. E. Phelps, and J. B. Crist. 1981. Wood and kraft pulping proerties of juvenile hybrid larch grown under intensive culture. (Abst.) In: Proc. 1981 TAPPI Annual Meeting, 1981 March 2-5, Chicago, Ill. TAPPI Press, p. 21.

Isebrands, J. G., D. W. Einspahr, J. E. Phelps, and J. B. Crist. 1982. Kraft pulp and paper properties of juvenile hybrid larch grown under intensive culture. TAPPI J. 65(9): 122-126.

Isebrands, J. G., and E. A. Hansen. 1982. Intensively cultured poplar plantations for wood and energy. (Abst.) In: Biographies and Abstracts. The Sixth International FPRS Industrial Wood Energy Forum 82, 1982 March 8-10, Washington, D. C., p. 16.

Isebrands, J. G., and R. A. Parham. 1978. On the nature of surface dislocations on Populus tension wood fibers. IAWA Bulletin 1978/2-3:47 (Abst.)

Isebrands, J. G., and R. A. Parham. 1979. Effects of compression wood on kraft paper from short rotation, intensively cultured jack pine. Proc. 33rd Annual Meeting For. Prod. Res. Soc., San Francisco, Cal. July 8-12, 1979, p. 5 (Abst.)

Isebrands, J. G., J. A. Sturos, and J. B. Crist. 1979. Integrated utilization of biomass--A case study of short rotation intensively cultured Populus raw material. TAPPI 62(7): 67-70.

Kandeel, S. A. E., J. G. Isebrands, and H. M. Aly. 1982. Windbreak-grown Casuarina and Eucalyptus trees for unbleached kraft pulp. Wood and Fiber 14: 287-295.

Neuman, Ronald D. 1976. Pulp and paper characteristics of Populus hybrids. In: Intensive plantation culture--five years research. USDA For. Serv. Gen. Tech. Rep. NC-21, p. 112-114. North Cent. For. Exp. Stn., St. Paul, Minn.

Parham, R. A., K. W. Robinson, and J.G. Isebrands. 1977. Effects of tension wood on kraft paper from a short rotation hardwood (Populus Tristis #1). Wood Science and Technology 11: 291-303.

Phelps, J. E., D.W. Einspahr, J. G. Isebrands, and J. B. Crist. 1981. Short rotatation intensively cultured hybrid larch a potential source of kraft pulp. (Abst.) FPRS 35th Annual Meeting, 1981 June 21-25, St. Paul, Minn., p. 41-42.

Phelps, J. E., J. G. Isebrands, D. W. Einspahr, and J. G. Crist. 1982. Kraft pulping of biomass components from intensively cultured poplar trees. (Abst.) Proc. FPRS 36th Annual Meeting, 1982 June 20-24 New Orleans, La., p. 26.

Phelps, J. E., J. G. Isebrands, and D. Jowett. 1982. Raw material quality of short rotation, intensively cultured Populus clones. I. A comparison of stem and branch properties at three spacings. IAWA Bull. 3: 193-200.

Phelps, J. E., J. G. Isebrands, and N. D. Nelson. 1982. Utilization potential of SRIC poplar raw material--a status report. (Abst.) In: Proc. North American Poplar Council Meeting, 1982 July 20-22, Rhinelander, WI, p. 134.

Zarges, R. V., R. D. Neumann, and J. B. Crist. 1980. Kraft pulp and paper properties of Populus clones grown under short rotation intensive culture. TAPPI 63: 91-94.

A PROTOTYPE HARVESTER FOR SHORT-ROTATION PLANTATIONS

James A. Mattson[1]

Michael A. Wehr[2]

Abstract.--A promising approach to increasing the supply of wood fiber for pulp and energy is short-rotation intensively cultured (SRIC) forestry. To apply the principles of agriculture to the growing of wood fiber, designers of harvesting equipment must consider a unique set of operating criteria. This paper summarizes the design criteria relevant to the SRIC concept and describes the results of initial trials with a prototype short-rotation harvester.

INTRODUCTION

Short-rotation intensively cultured (SRIC) plantations are a promising way to increase the supply of wood for fiber and energy in the future (U.S. Department of Agriculture, Forest Service 1980). To be applied commercially, SRIC systems must have technically and economically feasible equipment and systems to carry out the required silvicultural treatments and perform the necessary harvesting and processing operations.

The harvesting of wood fiber grown on SRIC plantations has received little attention. One advantage of SRIC systems is a completely mechanized harvesting operation to reduce labor costs and make a year-round operation more practical, but the mechanics of implementing the harvesting have not been extensively studied.

The forest engineering project at the Forestry Sciences Laboratory, Houghton, Michigan, has designed and fabricated a prototype harvester for SRIC plantations. This prototype is basically a test rig to evaluate the feasibility of several equipment concepts included in its design and also to develop a base of design criteria for an eventual commercial harvester.

[1]Principal Mechanical Engineer, USDA Forest Service, North Central Forest Experiment Station, Houghton, Michigan.

[2]Mechanical Engineer, USDA Forest Service, North Central Forest Experiment Station, Houghton, Michigan.

CHARACTERISTICS OF SRIC PLANTATIONS RELEVANT TO HARVESTER DESIGN

Short-rotation intensively cultured forests are expected to consist of selected, rapidly growing, hardwood tree species. The crop would be harvested at appropriate rotations, and the succeeding crops would arise by coppicing (sprouting from stumps), precluding the need to replant after each harvest.

Suggested plantation scenarios have row spacings ranging from 1.2 to 2.4 m with spacings between trees within the rows ranging from 1.2 to 1.8 m. Anticipated rotation age ranges from 8 to 15 years depending upon the spacing option chosen. These combinations will produce trees ranging from 10 to 25 cm in diameter at groundline and from 10 to 20 m tall. Most of the trees will be in the 10- to 20-cm diameter range, but some along the edges of the plantation may reach 30 cm in diameter. These stands are expected to produce from 10 to 15 dry tonne equivalents of biomass per hectare per year from trees ranging from less than 50 kg to more than 200 kg in the first harvest. Tree size will decrease with successful coppicing of the stands, and number of trees per hectare will increase.

Most envisioned SRIC systems use coppicing to regenerate the stand after harvesting. To ensure a suitable level of regeneration, the harvester will be required to maintain a preset stump height, up to 25 cm. The stump must have a clean-cut surface (such as would be produced with a saw). Lateral pressure against the stump will have to be minimized to avoid disturbing roots below ground. The harvester will have to stay within the rows of the plantation to avoid damaging the stump system.

Because the coppicing of the original stumps to produce new sprouts may produce a wider plant structure in subsequent harvests, the harvester will have to be able to handle a sprout cluster up to about 65 cm wide.

The need to obtain an adequate level of coppicing may limit the harvest season to the dormant season when ground conditions may be adverse. To aid mobility of the harvest equipment and avoid excessive damage to the site and root system, vehicle ground pressure will have to be minimized, possibly to as low as 15 to 20 kPa in extremely low bearing sites. The number of vehicle passes over the stand during harvest should also be minimized to avoid rutting, soil compaction, and other site damage.

Most sites envisioned for energy farms contain terrain suitable for vehicle travel. The harvester will probably only have to be capable of operating on side slopes up to 10 percent and direct slopes up to 20 percent. The plantations will also probably be free of rocks in the operating zone of the harvester felling device.

APPLICATIONS OF CONVENTIONAL EQUIPMENT

The biomass produced in SRIC forests may be handled and transported as whole-tree chips. The chips are suitable for most subsequent conversion and processing operations.

Whole tree chipping is a highly mechanized system capable of producing large quantities of wood per man-day. Besides the advantages of high productivity and reduced labor requirements, the yield per hectare of usable wood is greatly increased due to the additional amounts of fiber recovered from the tops, limbs, and other residue materials normally left in the woods after a conventional roundwood operation. Additionally, the site is left in a clean, esthetically more acceptable condition that facilitates subsequent silvicultural operations.

The basic whole-tree chipping system consists of feller/bunchers that sever the trees and accumulate them into bunches, grapple skidders that move the bunches from the forest to the chipper, portable chippers that operate at a woods landing to reduce the whole trees to chips, and chip vans that transport the chips to the mill (fig. 1).

An earlier study by Mattson (in preparation) used simulation methods to study the potential for utilizing whole-tree chipping to harvest SRIC plantations. The results of the simulator trials showed that tree size is the major factor affecting productivity and cost. Current harvesting equipment requires large trees to operate economically.

The felling/bunching phase of the harvesting operation is the area where current technology is the most deficient with respect to harvesting small trees. Current skidding/forwarding and chipping equipment is designed for multiple-tree operation, so it can be adjusted to the design parameters presented by the small trees of an intensively cultured stand. However, the basic design of conventional shears is based on handling one tree at a time. For stands of small trees, this restriction limits the potential productivity of the equipment.

The development of felling/bunching equipment that operates on a continuous or multitree basis is the most significant research need in the area of harvesting SRIC fiber.

HARVESTER CONCEPT CONSIDERATIONS

The requirement of coppicing to produce subsequent crops from the original stumps in SRIC plantations may preclude the use of a conventional whole-tree harvesting system as discussed previously. Preliminary studies have shown that the small stumps found in SRIC plantations are susceptible to mechanical damage by equipment working in the stand (Crist et al. in this proceedings). Skidding in particular, as it is typically done, would be unacceptable in an SRIC stand because the machine's maneuvering and turning would certainly cause excessive damage. Skidding the loads of trees across the plantation would also be likely to cause excessive damage. Because of the possibilities of damage, harvesting operations would probably have to be laid out so that whatever machinery is involved can stay tracked between rows of the plantation and carry out its required function while making a pass through the plantation.

The number of passes through the stand should also be minimized to minimize soil compaction---so a machine needing only one pass would be desirable. Such a machine would be capable of severing the stems and simultaneously collecting the severed stems and forwarding them to the plantation edge.

A machine that could simultaneously fell and chip the trees and transport the chips to the plantation edge would be much heavier than a machine that only fells and collects the severed trees and forwards them to the plantation edge. The lighter machine could be expected to cause less soil compaction and cost less. Considering that the harvester will probably be used only for a portion of the year,

a smaller, less costly machine would be preferable. If the harvester could be built to utillize a standard prime mover as its motive and functional power source, it could cost even less.

The possibility of the harvest being limited to the dormant season has some definite implications for the design of the harvesting equipment because the fiber must be stored for year-round use. Storing the material on the edge of the plantation would eliminate any initial transport because the harvester could offload right at the storage site, also eliminating the need for extensive storage at the use point. The harvesting would also be more efficient because any delays caused by interaction with the transportation system would be eliminated.

From the utilization standpoint, collecting the whole trees at the plantation edge for storage appears to have some advantages over chipping the material in the stand and then storing the chips. Also, chips are not a preferred form for long-term storage because problems with heating of the chip piles and deterioration of the material can occur. Dirt and grit can get into the material when chips are recovered from the ground for loading and subsequent transport to a use point. If the trees are stored in whole-tree form at the plantation edge, conventional chipping equipment can efficiently convert them into chips and load the chips onto trucks for transport. Also, the whole trees could be converted into an alternate product form such as chunks or blocks, which may be preferred for a particular application such as burning (Arola et al. in this proceedings).

A PROTOTYPE SRIC HARVESTER

The prototype harvester is composed of three major parts: a felling head, a directional felling device, and an accumulating section (fig. 2). The felling head on this prototype is constructed around an elongated two-flute milling cutter with spiral cutting edges, or auger cutter (fig. 3). It severs the stems by milling out a section of the trunks equal to the cutter diameter, 5 cm in the case of this prototype. The advantages of this device include the ability to cut anywhere along its 0.6 m length, no need for an anvil, and a fairly clean cut on the residual stump. The cutter is relatively heavy and compared to a circular saw, shouldn't be as vulnerable to damage from occasional contact with foreign objects or require sharpening as often.

The auger cutter is mounted in a movable subframe assembly that also contains the auger drive motor and a cutting height adjustment feature. The movable subframe assembly is mounted to the harvester in such a way as to allow relative motion in the direction of harvester travel between the harvester and the auger cutter. This is accomplished by the use of two guided shafts that form part of the forward section of the movable subframe. Each shaft is supported by two linear motion bearings contained on the rear section of the assembly. The rear section is pinned to the harvester to allow for different auger cutter height settings and to permit the subframe to float over irregular ground contours. The interface between the forward and rear sections of the auger cutter subframe assembly, in addition to the linear motion bearing and shafts, is two air cylinders. These cylinders keep the forward section extended to its outmost position and provide three functions: First, they allow for the setting of the maximum lateral load applied to the tree during the cutting process; this factor controls the chip thickness and horsepower requirements of the auger cutter. A large air reservoir incorporated in the harvester frame maintains an almost constant air pressure in the cylinders regardless of their relative position. Second, the cylinders allow for the forward section to return to the extended position once severing is completed. Their third and probably most important function is to allow for relative motion between the harvester main frame and the auger cutter. This is of utmost importance in obtaining good production rates. An ideal harvesting machine should be severing trees 100 percent of the time without any travel time between cuts. A rigidly fixed cutting device can require the harvester to slow during each cut and then speed up between cuts. The auger cutter retraction feature allows the cutter to sever the tree at its own rate while the main harvester frame travels at a steady rate along the row of trees. Production rates depend on tree spacing and size. The size or diameter of the tree determines the required cutting time which in turn will dictate the maximum harvester ground speed. By proper adjustment of the variables, cutter speed, feed pressure, and ground speed, the harvester would conceivably approach the 100-percent efficiency rate.

The cutting height adjustment feature consists of a pneumatic tire mounted on either side of the forward moving frame section adjacent to the end supports of the auger cutter. The wheels can be positioned so that stump heights will vary between 5 and 22 cm.

The cutter rotates upward so that stump damage is minimal during severing. The upward rotation also tends to move the butt of the tree rearward onto a shelf mounted behind the cutter. This shelf is an integral portion of

the forward-moving subframe. Once the tree is cut and placed in a vertical position on the support shelf, the directional felling device pushes and tips the tree towards the rear of the harvester. Guides direct the tree so that it falls to rest on the harvester bunks (wide U-shaped forms located at the front and rear of the harvester).

The directional felling device consists of two shafts mounted vertically on each side of the auger cutter. Each shaft has several spring steel blades mounted in a horizontal plane about the axis of the shaft. The shafts and blades rotate in opposite directions so that the cut portion of the tree is directed between the felling guides.

Once the tree has been felled onto the harvester bunks, slow-moving drag chains with tall fingers on each bunk move the tree towards the left side of the machine. When a small collection of trees has accumulated at the end of the drag chains, a packing arm on each bunk picks up the load and places it at the extreme left of the bunk and packs it, along with other small loads, into a bundle. Once a full load has been established in the packing area or at the end of a row of trees, the load is offloaded onto a pile for storage and subsequent processing and/or transportation to the use point.

The harvester was constructed so that several processing concepts could be tested; therefore, a drive and power system was not included as part of the main machine. Because most woods-working equipment is hydraulically operated, we decided that the harvester should also function hydraulically. To field test the harvester, all we needed to do was obtain the use of a prime mover with adequate hydraulic power and capacity to operate each of the harvester functions. Another advantage of a hydraulic system is the versatility of most hydraulic components. Motor and cylinder speeds can be controlled simply by monitoring and adjusting the oil flow to them. Motor torques and cylinder forces can be controlled by simply regulating the oil pressure. Because these controlling and regulating devices are commonly installed as part of a standard system, additional components are not necessary. If an entirely mechanical system were incorporated, then additional belts, pulleys, and other components would be necessary to vary the system functions.

Briefly, the harvester's functions are controlled by the following devices; the auger cutter is driven by a Abex-Dennison[3] spring vane motor, Model M4C. The motor is capable of 2500 psi at 2500 rpm continuous operation and 2500 psi at 4000 rpm intermittent. Because the motor is of a cartridge construction, various torque and speed combinations can be obtained. The "egg beaters" or directional felling devices are driven by Char-Lynn hydraulic motors, Model "H" of the gerotor design. The drag chains are operated by the same type of motor. The pack arms are controlled by hydraulic cylinders.

RESULTS OF INITIAL TESTS

Once the "bugs" were worked out of the auger cutting system, it performed remarkably well. The original auger cutter did not have enough chip space causing it to plug with chips and not feed properly. The cutter was reworked to deepen the gullet and enlarge the chip space. We also encountered problems with the first version of the auto retracting system and completely redesigned the sliding guides. With the auger running at 2000 rpm, the pressure relief set at 2500 psi, and with 60 psi in the air cylinders, the cutter cleanly severs a tree, leaving a relatively smooth stump surface. The forward moving frame section retracts effortlessly when vehicle speeds exceed the cutting speed.

The directional felling device was less successful; every so often a tree would not drop directly on the bunk. Usually the top of the tree would miss the rear bunk. Although this was not a serious problem, it could lead to delays and jams with a production-style machine. The bunk collection system (drag chain and packing device) worked as it was intended.

RECOMMENDATIONS FOR FURTHER RESEARCH

The harvester worked well for a first prototype, although several problems still exist in the directional felling phase. For this reason we are continuing with research into additional concepts for short-rotation harvesters. Presently, we are considering two concepts to combine the directional felling and collection phases into a single operation using an accumulator for collecting the trees in a vertical position behind the cutter. This approach could possibly increase the harvester's load carrying capacity while decreasing its physical size. Other concepts utilizing multirow harvesting will also be considered.

---

[3]The use of trade, firm, or corporation names in this publication is for the information and convenience of the reader. It does not constitute an official endorsement or approval of any product or service by the United States Department of Agriculture to the exclusion of others which may be suitable.

LITERATURE CITED

Mattson, James A. Harvesting developments for short-rotation intensively cultured forests. Manuscript in preparation.

U. S. Department of Agriculture, Forest Service. 1980. Energy & wood from intensively cultured plantations: research and development program. Gen. Tech. Rep. NC-58. St. Paul, MN. U.S. Department of Agriculture, Forest Service, North Central Forest Experiment Station. 28 p.

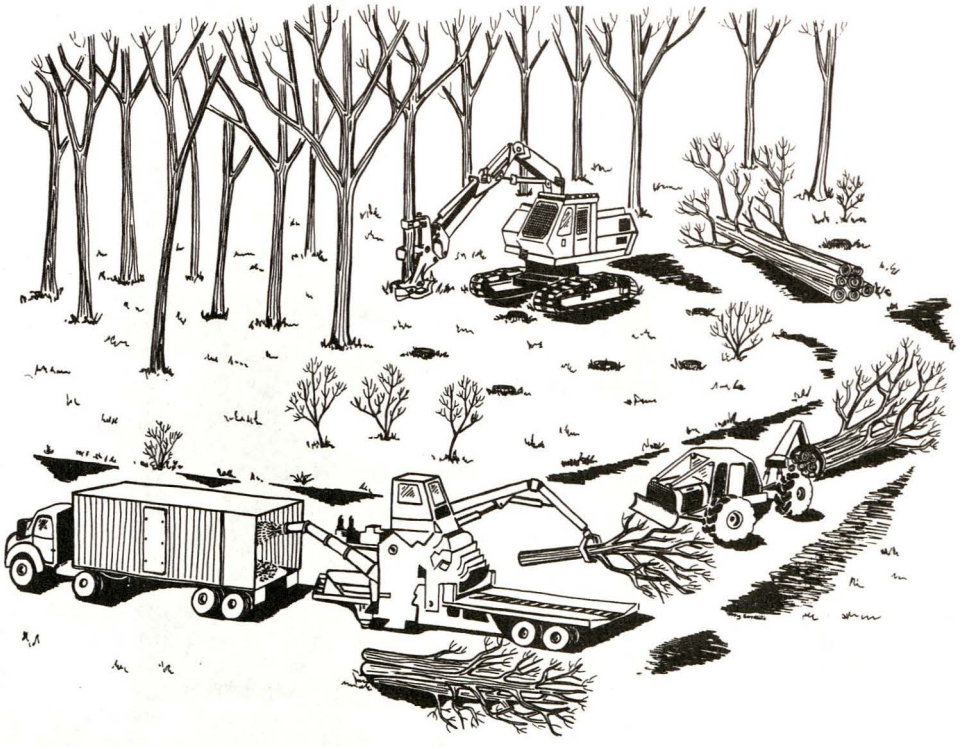


Figure 1.--Schematic of a typical whole-tree chipping operation.

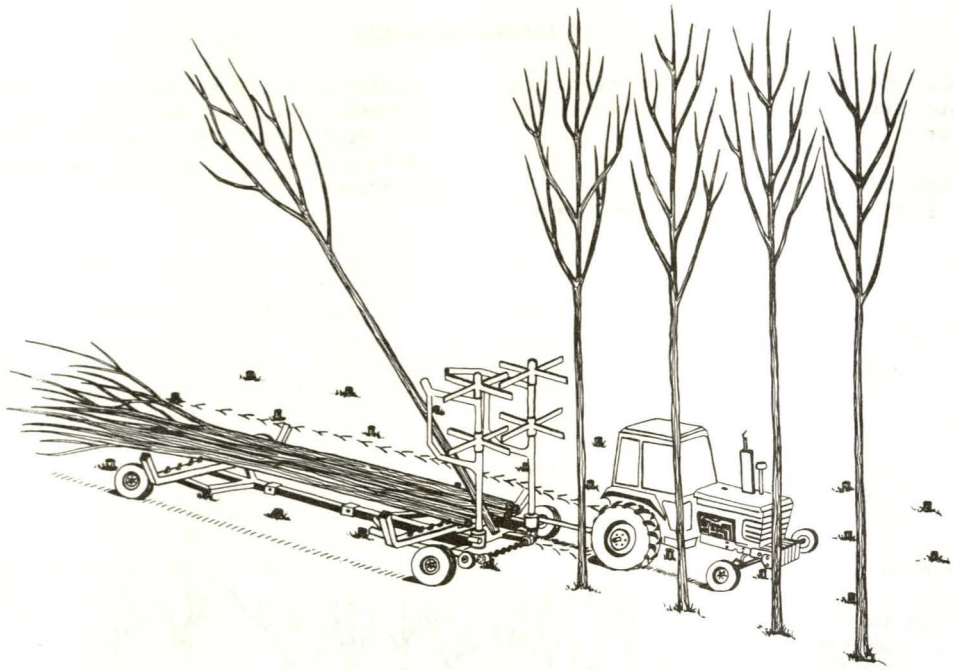


Figure 2.--A prototype SRIC harvester.

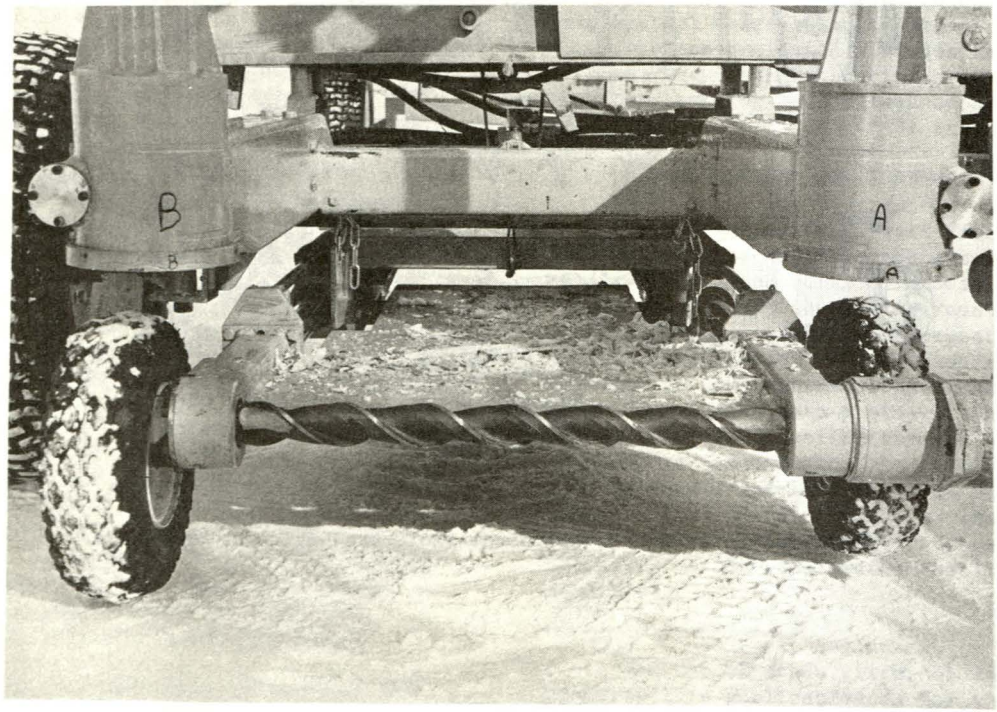


Figure 3.--Felling head of prototype SRIC harvester.

PROTOTYPE WOOD CHUNKER USED ON POPULUS 'TRISTIS'

Rodger A. Arola[1]

Robert C. Radcliffe[2]

Sharon A. Winsauer[3]

Abstract.--Populus 'Tristis' trees grown under short-rotation, intensive culture were sampled and chunked in a prototype experimental wood chunking machine. Data presented describe the character of the trees chunked, the energy and power requirements for chunking, and the chunking rate. Specific energy requirements for chunking Populus 'Tristis' are compared with chunking and chipping common Lake States' species from natural stands.

An essential objective of harvesting short rotation, intensively cultured (SRIC) plantations is to convert the trees into a useable form. Whole-tree chippers, which are commercially available, offer one means to reduce SRIC trees to chips for subsequent utilization for pulp and paper or energy. Although chips are used to produce energy they have several disadvantages due to their small particle size, low bulk density, and close layering characteristic that restricts air movement in storage piles or combustors that burn on grates. Chips are also not suitable as furnish for structural flakeboard because of their short dimensions in the fiber direction--they cannot be satisfactorily flaked.

To explore new utilization opportunities for small diameter trees including those from SRIC plantations, forest engineering researchers at the Forestry Sciences Laboratory in Houghton, Michigan, have been investigating new concepts for comminuting wood. A key result has been the development of a wood chunking machine that reduces small trees into particles much larger than chips. Our wood chunker is not yet commercialized, and we are just now introducing the wood chunking concept to industry. Thus, no data exist on the utilization of chunkwood in the composite wood material (CWM) and wood energy industries. Through future research and demonstration projects done in cooperation with industry and other interested organizations, we hope to document chunkwood's application to the wood energy and CWM industries.

Because of the excellent prospects for commercialization of our wood chunking concept, laboratory research was conducted on our prototype machine to determine overall performance and to document the power and energy requirements for several important Lake States' species (Arola et al. 1982; Arola et al., manuscript submitted to Forest Products Journal). The purpose of this paper is to provide similar documentation for chunking intensively grown Populus 'Tristis.'

CHUNKING TESTS AND RESULTS

Our basic wood chunker consists of three 1/4-inch curved blades attached to a driven, shaft-mounted disc (fig. 1). The blades, which vary in depth from zero at the leading edge to approximately 9 inches at the trailing edge, are mounted perpendicularly to the disc face with the trailing edges curved inward. Logs are fed into the blades by hydraulically powered feed rollers. As the disc rotates, the blades sever 2- to 5-inch long chunks from the bolts (fig. 2). We ran the machine at a no-load cutter disc speed of 220 revolutions per minute and a workpiece feed rate of 245 feet per minute.

Populus 'Tristis' samples were obtained from the North Central Forest Experiment Station's Harshaw Forestry Research Farm,

[1]Principal Mechanical Engineer, U.S. Department of Agriculture, Forest Service, North Central Forest Experiment Station, Houghton, Michigan.

[2]Mechanical Engineering Technician, U. S. Department of Agriculture, Forest Service, North Central Forest Experiment Station, Houghton, Michigan.

[3]Mathematician, U.S. Department of Agriculture, Forest Service, North Central Forest Experiment Station, Houghton, Michigan.

which is located near Harshaw, Wisconsin, and is managed by the Maximum Fiber Yield Project at Rhinelander, Wisconsin. All material was cut into nominal 100-inch bolts. For each test bolt we determined the small and large end diameters, moisture content, length, and weight (table 1).

By instrumenting the shaft, we were able to record torque, integral of torque, cutter disc speed, and time. From these measurements we calculated the energy per cubic foot of solid material chunked, average torque and horsepower required, and the chunkwood production rate (table 1).

In general, with bolts ranging in diameter from 3.5 to 7.5 inches, the machine chunked wood at the rate of about 30 cubic feet of solid wood per minute and required about 35 horsepower. The mean energy requirement for Populus 'Tristis', with a moisture content of 46 percent and specific gravity of 0.3, was 1.2 hp-min/cu ft.

It took less energy to chunk intensively cultured Populus 'Tristis' than it did to chunk several species from natural Lake States' stands including Populus 'Tristis' cousin, aspen (fig. 3). Though energy requirement data aren't available for conventional chipping of Populus 'Tristis,' the tabulations for aspen and maple clearly show that it takes less energy to produce chunks than chips (table 2).

Table 1.--Results of chunking tests with hybrid Populus 'Tristis.'[1]

Item	Mean	Standard deviation	Minimum	Maximum
Bolt length (inches)	100.2	1.6	99.0	105.0
Bolt diameter (inches)				
Small end	4.3	.5	3.6	5.0
Large end	6.1	.7	5.3	7.4
Weight (pounds)	44.8	11.1	31.3	62.2
Chunking time (seconds)	2.6	.2	2.4	3.2
Moisture content[2] (green basis)	46.5	3.8	40.5	52.5
Specific gravity	.3	.03	.24	.34
Production rate (cu-ft/min)	29.3	4.7	22.7	39.3
Average torque (ft-lb)	832.4	141.8	661.0	1,108.0
Average power (horsepower)	33.5	5.6	26.8	44.1
Energy				
(hp-min/cu ft)	1.2	.1	1.0	1.3
(hp-hr/green ton)	1.1	.1	.9	1.3
(hp-hr/ovendry ton)	2.1	.2	1.8	2.6

[1] Based on a cutter disc speed of 220 rpm and feed rate of 245 feet per minute.

[2] Calculated by TAPPI Standard T18 M-53 (Technical Association of Pulp and Paper Industries 1967).

Table 2.--Comparison of energy requirements for chunking versus chipping.

Species	Chunks	Conventional chips[1]	Energy ratio (chunks/chips)
	-hp-min/cu ft-		%
P.'Tristis'	1.2	--	--
Aspen	1.4	3.8	37
Red maple	2.1	5.5	38
Sugar maple	2.5	7.6	33

[1]Papworth and Erickson 1966.

We conclude that the concept of chunking and the prototype wood chunker have excellent commercial potential--both from wood utilization and equipment development viewpoints. The unique physical character and size appear to give chunkwood some distinct advantages over conventional pulp-size chips. Two key chunkwood opportunities are as an intermediate furnish for the flake board/composite wood product industries and the wood energy industry. We are currently cooperating with the Forest Products Laboratory in Madison, Wisconsin and the Institute of Wood Research at Michigan Technological University in Houghton, Michigan to evaluate the suitability of chunkwood as a source of flakes. This cooperative research focuses only on aspen and dense hardwoods. Similar research should be directed at Populus 'Tristis.' Because the wood energy industry has not yet been exposed to chunkwood as an energy converter feedstock, studies or demonstration projects should be carried out to evaluate the suitability of chunkwood for solid fuel combustors, gasifiers, pyrolyzers, etc. We are seeking the cooperation of the wood energy industry to document this application.

In our opinion, chunking will provide a viable alternative to chipping and will help improve the market potential for small trees from natural and SRIC stands.

LITERATURE CITED

Arola, Rodger A., Robert C. Radcliffe, Sharon A. Winsauer, Edsel D. Matson. 1982. A new machine for producing chunkwood. USDA Forest Service Res. Pap. NC-211. 8 p. North Central Forest Experiment Station, St. Paul, MN.

Arola, Rodger A., Sharon A. Winsauer, Robert C. Radcliffe, Martyn R. Smith. Chunkwood production: a new concept. Manuscript submitted to the For. Prod. J. for publication.

Papworth, R. L., J. R. Erickson. 1966. Power requirements for producing wood chips. For. Prod. J. 16(10): 31-36.

Technical Association of Pulp and Paper Industries. 1967. TAPPI standard T18 M-53.

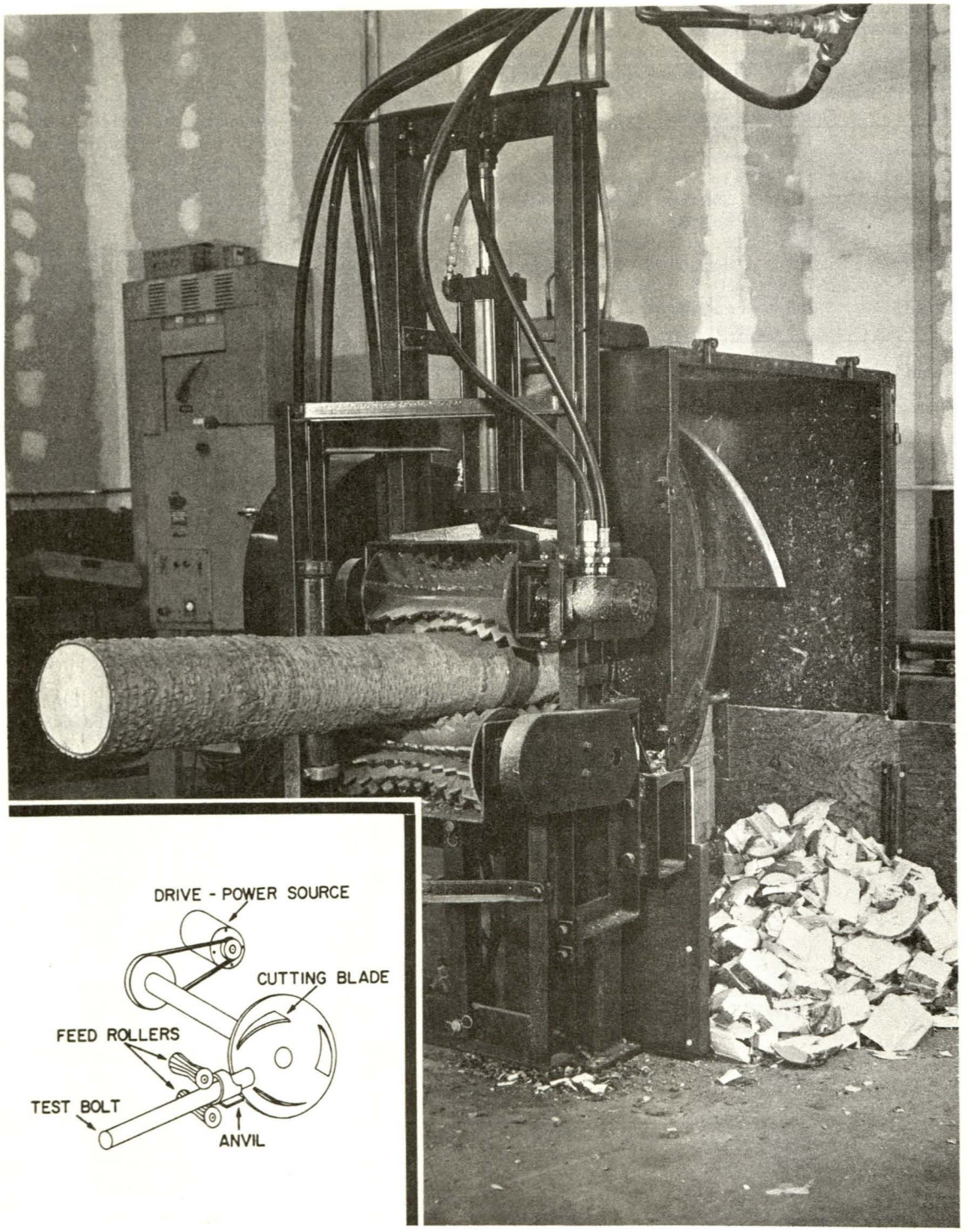


Figure 1.--Photo and simplified schematic of the experimental wood chunker.

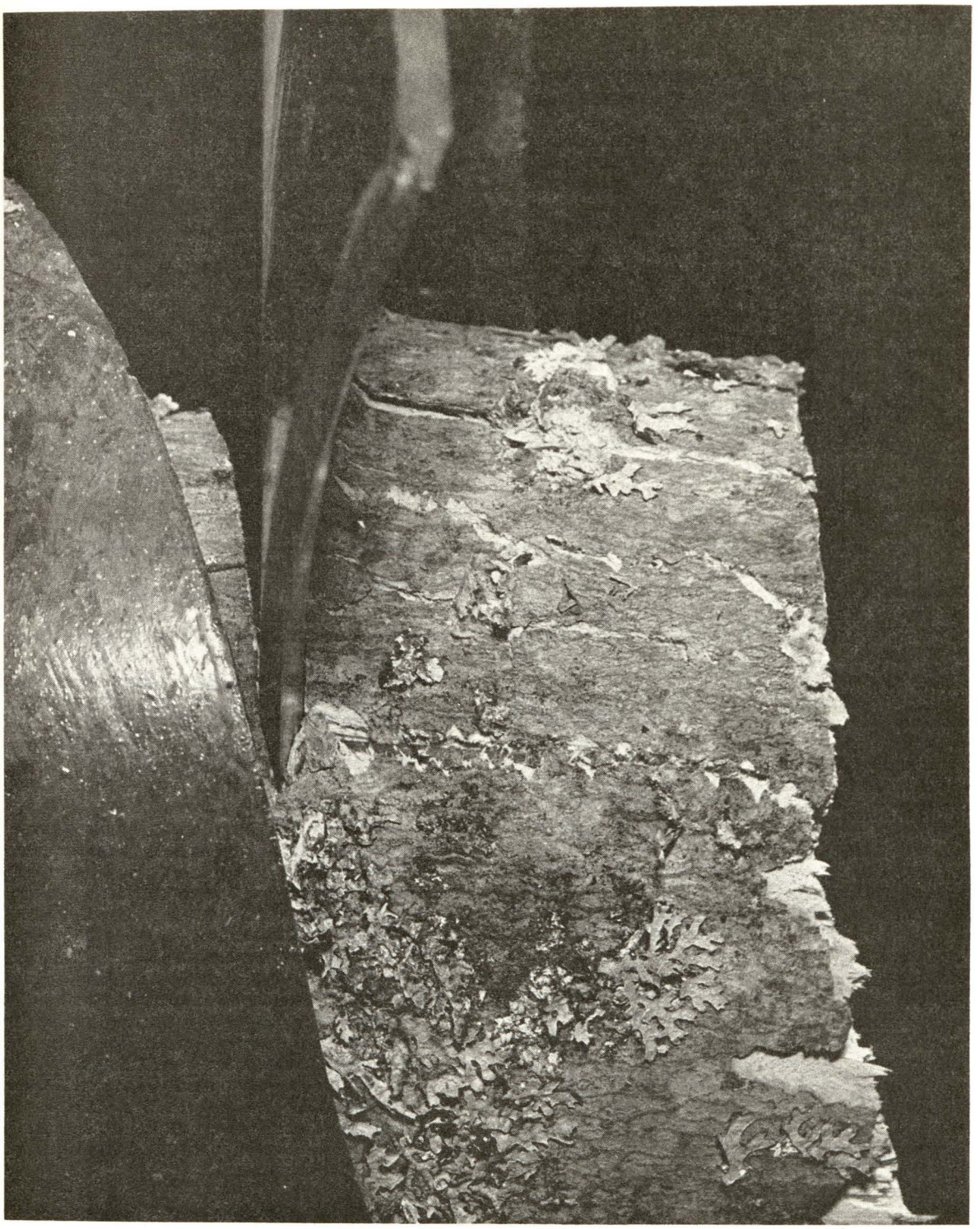


Figure 2.--Chunkwood being severed.

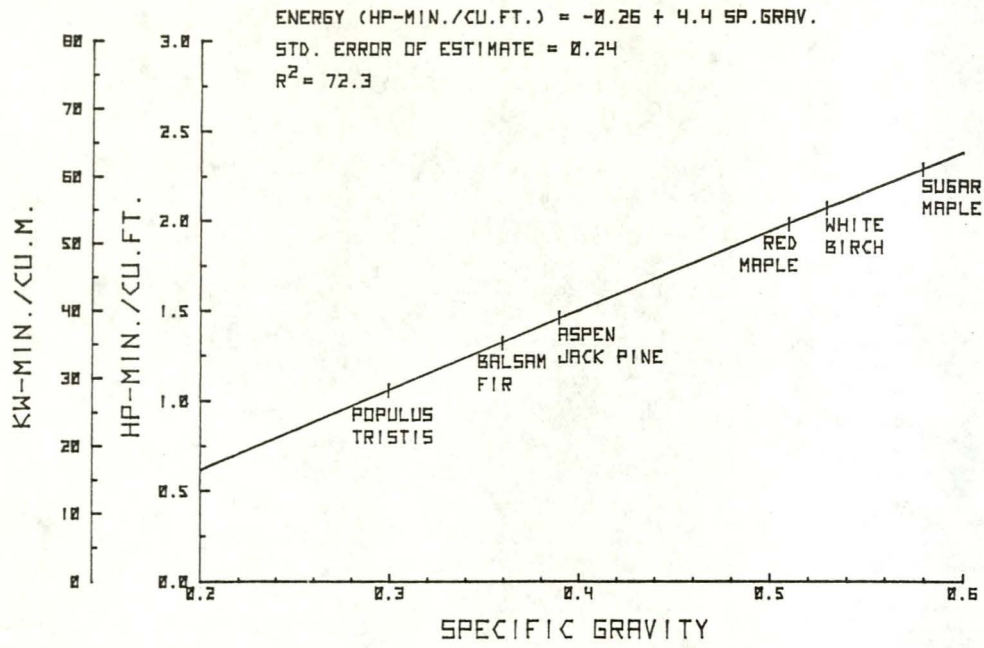


Figure 3.--Energy required to chunk several Lake States' species.

BIOMASS FROM INTENSIVELY CULTURED PLANTATIONS AS AN ENERGY, CHEMICAL, AND NUTRITIONAL FEEDSTOCK[1]

John E. Phelps[2]

Abstract.--Several technologies are described that have been developed to convert wood to fuel, chemicals or food products. Biomass from intensively cultured plantations has potential as a source of material for these energy related technologies. The technologies discussed here include: pyrolysis, gasification, liquefaction, hydrolysis, chemicals from lignin and hemicelluloses, and conversion of wood and foliage to ruminant animal feedstocks. Although these technologies show great promise, most need to become more economically attractive before they can be used on a large scale.

INTRODUCTION

One of the most pressing problems of our century is that of producing enough energy to maintain our current standard of living. Many reports indicate that we could run short of inexpensive, easily obtainable, and easily transportable energy in the near future. In fact, the first two concerns are already being realized.

During the past 50 to 100 years most of our energy needs have been met using petroleum-derived products. Before that, coal supplied much of the energy for our industrial revolution, and before coal, wood was used for many centuries. Wood and charcoal still supply much of the energy needs of the people in many developing countries (King 1980). However, the recent industrial development of the technologically advanced countries has centered around petroleum and petrochemicals and the products derived from them. Shrinking domestic supplies and concern over the ability to obtain petroleum from other countries have added to the uncertainty in obtaining needed energy sources.

Although there are no easy solutions to the energy problem, several ways have been proposed to alleviate some of the difficulties. These include: 1) conservation of resources; 2) recycling certain materials (e.g. aluminum and paper); 3) development of more fuel efficient vehicles and industrial methods; and 4) developing alternative sources of energy (e.g. nuclear, biomass, solar, wind, etc.). In addition, novel ways of using our resources have been developed. These include: 1) renovating old technologies (i.e. windmills, ethyl alcohol production from biomass, improving home designs, etc.) and; 2) developing new technologies (i.e. solar panels, deriving hydrogen from water, etc.) to reduce our energy dependence on traditional sources.

Biomass grown in intensively cultured plantations is a potential source of raw material for some of the developing energy technologies. Short rotation, intensive culture (SRIC) systems are designed to capitalize on the rapid growth potential of selected woody species by using near optimal growing conditions (Dawson 1979). SRIC plantations could be located in close proximity to industrial firms. At the Rhinelander Forestry Sciences Laboratory, we have examined the raw material quality of and certain products made from SRIC biomass in an attempt to determine product suitabilities. Our studies to date on more conventional wood and wood fiber products have produced encouraging results.

---

[1]Contribution from the Missouri Agricultural Experiment Station. Journal Series Number 9276

[2]Research Associate, School of Forestry, Fisheries and Wildlife, 1-30 Agriculture Building, University of Missouri, Columbia, Missouri 65211

This paper focuses on several ways of using biomass (potentially from SRIC plantations) to produce fuels and chemicals so that substitutes for petroleum based fuels and chemicals may be found. In addition, research at Rhinelander and elsewhere on substituting wood and foliage for traditional animal feedstocks will be described. Although the conversion technologies described here are somewhat general, in that they apply to most lignocellulosic (or higher plant) material or residues, it is assumed that SRIC material will behave in a similar manner.

Producing fuels and chemicals from biomass combines old and new technologies. For example, as mentioned before, ethyl alcohol production as a fermentation product from plant material has been practiced for many years. Newer technologies are directed toward developing more efficient and less costly means of producing chemicals like ethyl alcohol from plant biomass.

The conversion technologies discussed in this paper include: 1) pyrolysis - the conversion of wood to produce charcoal, liquids and gases; 2) gasification - the production of gases and subsequently methyl alcohol via combustion; 3) liquefaction - the production of higher hydrocarbon liquids (oils); 4) the production of ethyl alcohol via hydrolysis; 5) the production of other chemicals for the chemical industries; and 6) the production of animal feedstocks from wood and foliage.

PYROLYSIS AND GASIFICATION

Pyrolysis and gasification are part of the continuum of the thermal combustion process (Soltes and Elder 1981). Pyrolysis (destructive distillation) is conducted at temperatures below 600°C, in the absence of oxygen (Brink 1976), and yields charcoal and a volatile phase (Goldstein 1980). The charcoal produced by this method is a home fuel source in many developing countries, a major source of recreational cooking fuel in the United States, and is used as a coking medium in steel manufacturing in Brazil. The volatile phase can be separated into condensible liquids (pyrolignous acid, wood tars, acetone, acetic acid, and methyl alcohol) and several noncondensible gases (carbon dioxide, carbon monoxide, hydrogen and methane) (Goldstein 1980). However, gas yields from pyrolysis are not as high as those obtained during gasification. Large amounts of methyl alcohol (or wood alcohol) and acetic acid were derived from the pyrolysis process during the early part of this century (Goheen 1981). Recent studies show that vacuum pyrolysis of wood at reduced pressures (300 to 400 mm Hg) may be an economical way of producing wood oils. These oils would then be upgraded to chemicals by extraction and/or processing, while the char could be used for fuel for gasification or direct combustion (Anon. 1982).

Gasification of biomass is done at higher temperatures than pyrolysis (over 600° C) in the presence of oxygen (Brink 1976). The compounds that are formed during gasification are primarily carbon monoxide and hydrogen (called producer gas), but other gases, such as carbon dioxide, methane, and water vapor are also produced (Brink 1981, Goldstein 1980). Producer gas (gasogen, or low Btu-gas) can be burned as is (e.g. in "wood-powered" vehicles) or it can be upgraded to a synthesis gas (containing only carbon monoxide and hydrogen) and then converted to ammonia, methyl alcohol or methane. The production of methyl alcohol via the gasification process has been considered to be one of the more promising methods of producing chemicals from biomass (Reed 1980, Williams 1980). According to Reed (1980), methanol can be formed by compressing synthesis gas to 50-200 atmospheres and passing it over a chromium or copper oxide catalyst at 250 to 350° C. Methanol can either be used as an octane enhancer to produce high-octane gasoline (Goldstein 1980, Lee et al. 1980), as a gasoline extender in mixture with petroleum, as a stand alone fuel, or used to produce methane for heating fuel. The Ford Motor Company is testing methanol as an automotive fuel in 40 of their cars and they have observed no apparent technical or conversion problems (Annon. 1981a). However, the primary detrimental aspect of using methanol as an automotive fuel is that it is corrosive to some engine parts (Ofoli and Stout 1980, Williams 1980).

Methanol is also currently used in the production of formaldehyde, solvents, acrylics, insecticides, fungicides, and textile fibers (Rowell and Hokanson 1979). It can be used to produce methane using catalytic convertors operating at high pressures (Rowell and Hokanson 1979). This process, however, is quite energy intensive and requires further technological development to be economically feasible (Cheremisinoff 1980).

LIQUEFACTION

Liquefaction is the thermochemical conversion of biomass to fuel oils. As mentioned earlier, methanol can be produced from synthesis gas. Methanol can then be converted to oil

using the Fisher-Tropsch (Goldstein 1980) or the Mobil processes (Lee et al. 1980). This approach is called "indirect" liquefaction (Reed 1980).

In most cases, however, liquefaction refers to the production of fuel oil (also known as heavy oil, "proto-oil", or "protoproduct") directly from plant biomass. Although Berl (1944) was primarily describing work on non-woody plants, he indicated that "protoproduct" (with a higher heating value of 14000-15000 Btu per pound) can be derived from any carbohydrate containing material. This "protoproduct" could be used as a substitute for fuel oil or, following treatment, as diesel fuel.

More recently, Appell (1977), Boocock and Mackay (1980), Cheremisinoff (1980), Reed (1980), Miller and Fellows (1981), Petter et al. (1981), and Livingston (1982) have studied liquefaction with encouraging results. In those studies, the wood was ground-up or shredded, mixed with water, and converted to oil using a catalyst (nickel or sodium carbonate), elevated temperatures (250 to 400°C), elevated pressures (1500 to 3500 psig), and an atmosphere rich in carbon monoxide (CO). Apparently the CO removed part of the oxygen from the wood carbohydrates. The oil produced had a Btu content of 13000 to 17000 Btu per pound (Appell 1977), compared to wood with a Btu content of about 8500 Btu per pound and heating oil with a Btu content of 18000 Btu per pound (Livingston 1982). Pepper et al. (1981) and Livingston (1982) published reports on the liquefaction of aspen while Boocock and Mackay (1980) published on the liquefaction of fast growing hybrid poplar trees. All studies obtained good results; e.g. Livingston (1982) reported a 35% to 45% conversion of the dry wood mass to oil. This recovery is equivalent to approximately one to two barrels of oil from each ton of wood. Unfortunately, production costs of $50.00 a barrel must be reduced considerably for the liquefaction process to be economically feasible at the present price of oil.

HYDROLYSIS

Pyrolysis and gasification processes are, by nature, rather non-selective processes for the conversion of wood to chemicals (Goldstein 1981a) in that the whole woody biomass is reduced in a single step. Processes such as hydrolysis are more selective in that the wood is separated into its three main components -- cellulose, hemicelluloses, and lignin during processing. Each component is, in turn, converted to useful chemicals (Goldstein 1981a), energy, and food (Lora and Wayman 1979).

One method that has been proposed for the separation procedure involves two steps (Seaman 1980, Lyons 1981). In the first step, hemicelluloses are removed using a dilute acid, warm alkali or steam pretreatment and the lignin is removed by solvents (e.g. cadoxen) (Lyons 1981). Cadoxen has also been shown to disrupt the crystalline structure to cellulose and make it more susceptible to hydrolysis (Ladisch et al. 1978). In the second step, the cellulose is hydrolyzed by either enzymes or acids. Hemicelluloses, if left in the solution, produce pentose sugars and acetic acid which interfere with product purity (Lyons 1981) and inhibit fermentation of sugars to ethanol (Cheremisinoff 1980). In addition, pretreatment enhances the susceptibility of the cellulose to further hydrolysis by either chemicals or enzymes (Zerbe 1980).

Other advantages of pretreatment are: 1) acceptable sugar yields (48% to 50%) and a high concentration of sugar (10% to 12%) can be obtained; 2) pentoses can be derived in the first stage and glucose in the second; 3) steam can be used or if acids are used, there is a low consumption of the acid; and 4) small digestors can be used due to the short time of hydrolyzation (Saeman 1980). Apparently the use of a steam pretreatment is species dependent because Lyons (1981) observed that steam pretreatment rendered poplar wood more susceptible to enzyme activity, but softwoods were rendered less susceptible.

Hydrolysis is the selective conversion of the carbohydrate components of wood to their constituent sugars (Goldstein 1980). It can be accomplished via several different methods. Autohydrolysis is actually a specialized form of pretreatment in that high pressure steam or a steam explosion process is used to separate hemicelluloses and lignin from cellulose. Hanselmann (1982) considered steam explosion of wood to be a very efficient separation process. Steam explosion yields cellulose, hemicelluloses that are partially hydrolyzed, and low molecular weight lignin compounds. The cellulose can then be digested by microorganisms to form ethanol (Hanselmann 1982). The hemicelluloses can be further processed to make furfural and xylitol, fermented to alcohol via microorganisms (Williams 1980), or used as a substrate for yeast production (Saeman 1980). The lignin that is obtained by this process is in a highly reactive form that can be extracted under relatively mild conditions (Lora and Wayman 1979).

Acid hydrolysis has been used successfully since the turn of the century. This process gained considerable attention during the World Wars when sources of petroleum were

under siege. Following W. W. II, interest in acid hydrolysis declined but interest has been renewed in the 1970's due to escalating oil prices.

In the acid hydrolysis process, either hydrochloric or sulfuric acid is used. Hydrochloric acid is used in concentrated form while sulfuric acid can be used in either dilute or concentrated forms. Concentrated acids allow hydrolysis to be conducted at lower temperatures than dilute acids and they give higher yields. However, concentrated acids require expensive, non-corrosive equipment and higher costs for acid recovery systems (Goldstein 1981a). Dilute acid hydrolysis is less corrosive but gives lower yields and requires higher operating temperatures (Goldstein 1981a). In addition, although lignin has little effect on acid hydrolysis (Saeman 1979, Goldstein 1980), it is often rendered insoluble and unreactive following acid hydrolysis (Lora and Wayman 1979). Acid hydrolysis is one of the older technologies for converting biomass to various chemicals (Bungay 1982) and has the advantage of being applicable to most species of wood.

Enzyme hydrolysis is a third method for reducing cellulose to glucose and subsequently to ethyl alcohol. The enzymes (cellulases) for this process are derived from improved strains of wood decaying fungi and bacteria. Fungal enzymes have shown much promise in this reduction process. One of the fungi most suitable for large scale conversion of cellulose to glucose is Trichoderma reesei, a mutant of T. virida (Goldstein 1981a). Another organism that produces enzymes to convert cellulose to glucose is Aspergillus (Lyons 1981). Some organisms that hydrolyze glucose to ethanol include a yeast of Saccharomyces (Wiegel 1982) and bacteria of Clostridium (Wiegel 1982) and Thermonospora spp. The yeast, Pachysolen tannophilus, directly converts xylose (from hemicelluloses) to ethanol (Anon. 1981b). Another yeast, Candida tropicalis, converts xylose to ethanol under aerobic conditions (Jeffries 1981).

Although enzyme hydrolysis has been shown to give higher yields of glucose than acid hydrolysis (Lyons 1981), there are several problems inherent in its use. Research is now focusing on solutions to these problems. One problem is that most enzymes function best in a rather narrow temperature range. Enzymes are also negatively influenced by the high degree of crystallinity of cellulose and the high lignin content usually found in wood (Goldstein 1980). At present, the costs of these enzymes is also prohibitive, but these costs are declining and they may be more attractive in the future (Bungay 1982). In addition, the reaction time for the enzyme hydrolysis process is much slower than acid hydrolysis (Goldstein 1981a).

Glucose derived from hydrolysis can be converted to ethyl alcohol via fermentation (Lyons 1981), and ethyl alcohol can be converted to ethylene or butadiene, both important industrial chemicals (Goldstein 1980). Glucose can also be converted to a food that may be consumed by man or animals; to a feedstock to make solvents, plastics or other chemicals currently made from petroleum; or converted to single cell protein to be used as a food supplement (Lyons 1981).

OTHER CHEMICALS FROM BIOMASS

All chemicals in the wood should be fully utilized to make chemical utilization of wood economically feasible (Goldstein 1975). The best way to do this, as discussed above, is to separate the wood into its three main chemical components -- cellulose, hemicelluloses, and lignin, and make products from each component. The utilization of cellulose, via hydrolysis, has already been discussed. Although cellulose can be useful in producing materials such as glucose, single cell protein, etc., possibly its major benefit will come in the production of ethyl alcohol. Ethyl alcohol is currently being used as a motor fuel in Brazil and in some states in the United States. Ethyl alcohol is also an important intermediate to industrial chemicals, primarily ethylene and butadiene as mentioned above (Goldstein 1981a). Ethylene, butadiene, and phenol (from lignin) are the major building blocks for the production of synthetic polymers (Goldstein 1975).

Other chemicals can also be derived from hemicelluloses and lignin. According to Thompson (1981), hardwoods are composed of approximately 24% lignin, 48% cellulose, 3% glucomannan and 22% xylan with approximately 3% miscellaneous polymeric compounds. However, softwoods have a slightly different chemical composition with 29% lignin, 43% cellulose, 17% glucomannan, 8% xylan, and, again, 3% miscellaneous polymeric compounds. Xylan and glucomannan are two of the most important hemicelluloses in wood. Note that the relative proportions of each are reversed in hardwoods and softwoods. Aspen and hybrid poplar have been shown to have lower lignin contents than those hardwoods described above. Aspen has a lignin content of 16% to 21% (Dickson et al.

1974, Panshin and de Zeeuw 1980, Hajny 1981) while Populus hybrids have been shown to have an average lignin content of 21% (Dickson et al. 1974).

Chemicals derived from xylose, the hydrolyzate of xylan, include: D-xylose - useful for making food additives, detergents, or polyurethane; xylitol - useful as a sweetner, humectant, and plastic plasticizer; and furfural - useful in plastics, solvents and other chemical products (Thompson 1981). However, demand for mannose-derived chemicals, the hydrolyzate of glucomannan, is currently low and will remain low unless their price becomes more competitive with corresponding glucose-derived chemicals (Thompson 1981).

Phenols and other aromatic compounds can be derived from lignin and then used in synthetic polymer chemistry (Goldstein 1975). These aromatic compounds are of particular commercial interest because of their high market value (Hanselmann 1982). In addition, vanillin is routinely obtained from lignin sulfonates in spent sulfite liquors via alkaline hydrolysis with lime and sodium carbonate under carefully controlled partial pressures of oxygen (Goheen 1981). Vanillin is used for food flavorings and in the perfume industries (Goheen 1981). Unfortunately, if all hemicelluloses were converted to furfural and all lignin to phenols, the chemical market may not, at the present time, be able to absorb the large quantities obtained (Goldstein 1981b). Therefore, new markets for furfural and phenol will have to be developed.

ANIMAL FEEDSTOCKS FROM WOOD AND FOLIAGE

Although wood is made up of carbohydrate material, carbohydrates are often inaccessible to organisms that can reduce them into readily usable forms of energy. As mentioned earlier, the major reasons for this are the high degree of crystallinity of the cellulose and the high amounts of lignin present in wood. The presence of lignin in wood has been particularly effective in reducing the digestibility of wood to ruminant microorganisms (Hajny 1981, Scott et al. 1969).

Most work to date on this topic has been concerned with digestibility trials using ruminant animals. These animals require large amounts of vegetable matter in their diets. Research is aimed at supplementing their diets with wood feedstocks to extend the grain resource base.

Wood can either be used as a roughage (non-nutritive) material or as an energy food for ruminant animals (Scott et al. 1969). Use of highly concentrated cattle feeds require the addition of certain amounts of roughage so that the animal can maintain good health. Baker et al. (1975) considered 5 to 15% screened sawdust to be a practical roughage quantity in beef cattle rations.

However, the use of wood as an energy food for ruminants requires that wood be rendered more digestible. Because there is a direct relationship between the in vitro digestibility of wood and the degree of lignification (Hajny 1981), delignification of woody biomass is essential for improving digestibility. Populus wood has been shown, in some cases, to be relatively digestible without delignification, presumably because of its low lignin content (Kamstra 1979). However, delignification processes have been shown to improve the digestibility of Populus wood as well (Mellenberger et al. 1971).

Hajny (1981) and Satter et al. (1981) described several methods to increase the digestibility of wood. These include: electron radiation; vibratory ball milling; treatment with anhydrous ammonia, gaseous sulfur dioxide, or dilute sodium hydroxide; and use of pulping residues. Electron radiation, vibratory ball milling, and treatment with anhydrous ammonia, or dilute sodium hydroxide have been shown to increase the digestibility of hardwoods, but have little effect on the digestibility of softwoods (Hajny 1981, Satter et al. 1981). However, the use of gaseous sulfur dioxide does not exhibit this species specificity. The use of pulp residues will vary depending on the species and the pulping processes used. In general, screen rejects and pulp fines have acceptable digestibilities for ruminants (Hajny 1981).

All methods, in one way or another, influence biomass digestibility to varying degrees and have varying costs associated with them. From the standpoint of SRIC material, however, the results of digestibility trials of aspen are encouraging. Populus hybrids would probably behave similarly.

Autohydrolysis has been quite successful in the defibration of low density hardwoods (i.e. aspen). An autohydrolysis process developed by STAKE Technology Ltd. has shown particular industrial potential for the production of cattle feed supplements from the cellulose of native aspen.

The use of wood feedstocks also requires the addition of protein and other nutrients (Satter et al. 1981) before they would become an acceptable dietary supplement. In addition, the preparation of animal feedstocks from wood may require cost reductions to be competitive.

Although the discussion thus far has centered around uses of woody material as a fuel, energy or nutritional material, another possible product from SRIC plantations is commercial foliage.

An analysis of the chemical composition of hand-picked foliage from Populus hybrid clones indicated that this material was high in protein and could be used as a high quality livestock feed supplement (Dickson and Larson 1977a, 1977b). As a result of these analyses, further research has been devoted to the mechanical separation of leaves and commercial foliage from hybrid poplar trees.

Two methods that have been examined to date are the Morbark commercial foliage separator and the vacuum airlift segregator (VAS) (Crist et al. 1979, Isebrands et al. 1979, Nelson 1982[3]). The VAS has vacuum settings which can be adjusted to separate wood, bark, and leaf material that is riding on a wire mesh conveyor belt. The VAS was developed by the Forestry Sciences Laboratory at Houghton, Michigan (Arola et al. 1976, Sturos 1978, Sturos and Dickson 1980). Digestibility trials of VAS separated commercial foliage have shown particular promise (Crist et al. 1979) especially when the VAS is adjusted for maximum leaf separation (Nelson 1982[3]). In addition to high digestibilities, the VAS commercial foliage is high in protein and could possibly be used as a low-cost protein supplement in ruminant animals (Nelson 1982[3]). Further analyses are being done, and the results are encouraging.

SUMMARY

Woody biomass and woody residues offer much potential as a source of material for fuel, chemical and nutritional feedstocks. These raw materials are readily available in large quantities in this country, they are renewable, and in the case of intensively cultured plantations, they can be cultivated in areas close to where they are needed to provide maximum return.

A great deal of research has been done on the technological aspects of converting biomass to these energy and food related products. Apparently many of the technical problems have been solved. However, what is currently needed are ways to make these technologies more economically attractive. Biomass grown in intensively cultured plantations offers a new and attractive source of material for these promising technologies.

[3]Nelson, N. D. 1982. Personal Communication.

LITERATURE CITED

Anonymous. 1981a. Biomass Digest 3(3):1.

Anonymous. 1981b. Inside R and D 10(30):2.

Anonymous. 1982. Biomass Digest 4(12):5.

Appell, H. R. 1977. The production of oil from wood waste. In Fuels from Waste (L. L. Anderson and D. A. Tillman, eds.) Academic Press, New York. Pages 121-140.

Arola, R. A., J. A. Sturos, and J. A. Mattson. 1976. Research in quality improvement of whole-tree chips. TAPPI 59(7):66-70.

Baker, A. J., M. A. Millett, and L. D. Satter. 1975. Wood and wood-based residues in animal feeds. In Cellulose Technology Research (A. F. Turbak, ed.). ACS Symposium Series 10, Amer. Chem. Society, Washington, D. C. Pages 75-105.

Berl, E. 1944. Production of oil from plant material. Science 99(2573):309-312.

Boocock, D. G. B., and D. Mackay. 1980. The production of liquid hydrocarbons by wood hydrogenation. IGT Symposium - Energy from Biomass and Wastes IV. Jan. 21-15, 1980. Lake Buena Vista, Florida. Pages 765-777.

Brink, D. L. 1976. Pyrolysis-gasification-combustion: A process for utilization of plant material. Applied Polymer Symposium 28: 1377-1391.

Brink, D. L. 1981. Gasification. In Organic Chemicals From Biomass. (I. S. Goldstein, ed.). CRC Press, Inc., Boca Raton, Florida. Pages 45-62.

Bungay, H. R. 1982. Biomass refining. Science 218:643-646.

Cheremisinoff, N. P. 1980. Wood for energy production. Energy Technology Series. Ann Arbor Science Publications, Inc., P.O. Box 1425, Ann Arbor, Michigan 48106. 152 pages.

Crist, J. B., J. G. Isebrands, and N. D. Nelson. 1979. Suitability of intensively grown Populus raw material for industry. In Proceedings 16th Annual North American Poplar Council Meeting. Pages 65-74.

Dawson, D. H. 1979. Research and development of intensively cultured plantations for maximum biomass production. In Proceedings Third Annual Biomass Energy Conference, June 1979. National Biomass Program, SERI, Golden, Colorado. Pages 359-365.

Dickson, R. E., and P. R. Larson. 1977a. Leaf chemical composition of twenty-one Populus hybrid clones grown under intensive culture. In Proceedings Tenth Central States Forest Tree Improvement Conference. Purdue University, West Lafayette, Indiana. Pages 20-29.

Dickson, R. E., and P. R. Larson. 1977b. Muka from Populus leaves: a high-energy feed supplement for livestock. In Proceedings TAPPI Forest Biology Wood Chemistry Conference. Madison, Wisconsin. Pages 95-99.

Dickson, R. E., P. R. Larson, and J. G. Isebrands. 1974. Differences in cell-wall chemical composition among eighteen three-year-old Populus hybrid clones. In Proceedings Ninth Central States Forest Tree Improvement Conference. October 10-11, 1974. Ames, Iowa. Pages 21-34.

Goheen, D. W. 1981. Chemicals from lignin. In Organic Chemicals From Biomass. (I. S. Goldstein, ed.), CRC Press, Inc., Boca Raton, Florida. Pages 143-161.

Goldstein, I. S. 1975. Potential for converting wood into plastics. Science 189 (4206):847-852.

Goldstein, E. S. 1980. New technology for new uses of wood. TAPPI 63(2):105-108.

Goldstein, I. S. 1981a. Chemicals from Cellulose. In Organic Chemicals From Biomass (I. S. Goldstein, ed.), CRC Press, Inc., Boca Raton, Florida. Pages 101-124.

Goldstein, I. S. 1981b. Integrated plants for chemicals from biomass. In Organic Chemicals from Biomass. (I. S. Goldstein, ed.), CRC Press, Boca Raton, Florida. Pages 281-285,

Hajny, G. J. 1981. Biological utilization of wood for production of chemicals and foodstuffs. USDA Forest Service Research Paper FPL 385. 65 pages.

Hanselmann, K. W. 1982. Lignochemicals. Experientia 38(2):176-188.

Isebrands, J. G., J. A. Sturos, and J. B. Crist. 1979. Integrated utilization of biomass: A case study of short-rotation intensively cultured Populus raw material. TAPPI 62(7):67-70.

Jeffries, T. W. 1981. Conversion of xylose to ethanol under aerobic conditions by Candida tropicalis. Biotechnology Letters 3(5):213-218.

Kamstra, L. D. 1979. Aspen as a livestock feed. Termination Report, South Dakota State University Research Project, Old West Regional Commission Grant. South Dakota State University. Brookings, South Dakota. 7 pages

King, G. 1980. Wood for energy. Commonwealth Forestry Review 59(2):181-192.

Ladisch, M. R., C. M. Ladisch, and G. T. Tsao. 1978. Cellulose to sugars: New path gives quantitive yield. Science 201:743-745.

Lee, W., J. Maziuk, V. W. Weekman, Jr., and S. Yurchak. 1980. Catalytic conversion of alcohols to gasoline by the Mobil process. IGT Symposium. Energy From Biomass and Wastes IV. Lake Buena Vista, Florida. Jan. 21-25, 1980. Pages 721-745.

Livingston, M. 1982. Proto-oil grows on trees. Canadian Forest Industries 102(6):8.

Lora, J. H., and M Wayman. 1979. Fast-growing poplar: A renewable source of chemicals, energy and food. In Poplar Research Management and Utilization in Canada (D. C. F. Fayle, L. Zsuffa, and H. W. Anderson, eds.), Ontario Ministry of Natural Resources, Forest Research Information Paper No. 102. 9 pages.

Lyons, T. P. 1981. Cellulose as a raw material. Gasohol U.S.A. (February), Pages 14-15, 17-18, 27-28.

Mellenberger, R. W., L. D. Satter, M. A. Millet, and A. J. Baker. 1971. Digestion of aspen, alkali-treated aspen, and aspen bark by goats. Journal of Animal Science 32:756-763.

Miller, I. J., and S. K. Fellows. 1981. Liquefaction of biomass as a source of fuels or chemicals. Nature 289:398-399.

Ofoli, G. and B. Stout. 1980. Methanol for fuel. Agricultural Engineering Information Series No. 442. Michigan State University. East Lansing, Michigan. 13 pages.

Panshin, A. J., and C. de Zeeuw. 1980. Textbook of Wood Technology, Fourth Edition. McGraw-Hill Book Company, New York, 722 pages.

Pepper, J. M., R. L. Eager, and J. F. Mathews. 1981. Study of the conversion of lignocellulose (aspen) materials to liquid fuels and chemicals. Canadian Forestry Service. Environment Canada, ENFOR project C-48(1). Contractor's Final Report. 31 pages.

Reed, T. B. 1980. The combustion, pyrolysis, gasification and liquefaction of biomass. Paper presented at the "Energy from Biomass Conference". Brighton, England, Nov. 4-7, 1980. SERI/TP-622-893. 14 pages.

Rowell, R. M. and A. E. Hokanson. 1979. Methanol from wood: A critical assessment. In Progress in Biomass Conversion, Vol. 1. (K. V. Sarkanen and D. A. Tillman, eds.) Academic Press. New York. Pages 117-144.

Saeman, J. F. 1979. Key factors in the hydrolysis of cellulose. In Symposium on Biomass as a Non-fossil Fuel Source. Division Petroleum Chemistry, Inc., Joint Meeting of the American Chemical Society and the Chemistry Society of Japan. Honolulu, Hawaii. April 1-6, 1979. Pages 472-480.

Saeman, J. F. 1980. Assessment of dilute acid hydrolysis of cellulose. In Proceedings Bio-Energy '80 World Congress and Exposition, Atlanta, Georgia. April 21-24, 1980. Pages 162-164.

Satter, L. D., A. J. Baker, and M. A. Millett. 1981. Increasing the nutritive value of wood and forest products through chemical and physical treatments. In Upgrading Residues and By-products for Animals. CRC Press. Pages 61-76.

Scott, R. W., M. A. Millett, and G. J. Hajny. 1969. Wood wastes for animal feeding. Forest Products Journal 19(4):14-18.

Soltes, E. J., and T. J. Elder. 1981. Pyrolysis. In Organic Chemicals from Biomass. (I. S. Goldstein, ed.). CRC Press, Inc., Boca Raton, Florida. Pages 63-99.

Sturos, J. A. 1978. Bark. foliage and grit removal from whole-tree chips - results and economics. In Proceedings TAPPI Pulping Conference, New Orleans, Louisiana. Pages 121-124.

Sturos, J. A., and R. E. Dickson. 1980. Fiber, fuel, and food from whole-tree chips. Transactions of the ASAE 23:1353-1358.

Thompson, N. S. 1981. Chemicals from hemicelluloses. In Organic Chemicals from Biomass. (I. S. Goldstein, ed.) CRC Press, Inc., Boca Raton, Florida. Pages 125-141.

Wiegel, J. 1982. Ethanol from cellulose. Experientia 38:151-156.

Williams, J. 1980. Biomass research: A survey of recent US government efforts. UNASYLVA 32(128):33-34.

Zerbe, J. I. 1980. Wood and the energy crisis. Forest Farmer 39(5):12-15.

ECONOMIC INVESTIGATIONS OF SHORT ROTATION INTENSIVELY CULTURED HYBRID POPLARS

David C. Lothner[1/]

Abstract.--The history of the economic analyses is summarized for short rotation intensively cultured hybrid poplar at the North Central Forest Experiment Station. Early break-even analyses with limited data indicated that at a price of $25-30 per dry ton for fiber and low to medium production costs, several systems looked profitable. Later cash flow analyses indicated that two systems without irrigation and fertilization could achieve internal rates of return of 8 percent with a 5 percent inflation rate. However, two systems with irrigation and fertilization had negative internal rates of return. All systems had negative net present values when a 10 percent discount rate was used. We are currently incorporating risk analysis into our financial investigation to directly account for uncertainty in the performance calculations.

During the last several years interest has increased remarkably in intensive agronomic techniques to produce high yields of woody biomass for energy and fiber. And our knowledge and experience through many studies and field trials has been increasingly encouraging. Land managers and scientists in both the public and private sectors are facing several important decisions.

For the land manager few tasks are more challenging than developing a production plan to meet future mill requirements. Options include: investing in intensive culture short-rotation (SRIC) forest plantations, investing in conventional less-intensive longer rotation forest plantations, or purchasing the wood as needed on the open market. If a decision is made to invest in SRIC forest plantations, how intensively should these plantations be managed and which of numerous management perscriptions should be followed?

For the scientist it takes time to develop information about specific management alternatives and the number of possible management alternatives is enormous. Scientists must decide which aspects--site preparation, planting, post-planting release, etc.--of the overall management system merit further study in order to improve performance.

The economist can aid both. He can aid the manager with financial analysis models that describe cost and return relations, determine capital requirements, and calculate financial performances of alternative projects. He can aid both manager and scientist by pointing out the importance of the various activities to the overall financial performance. And, finally, he can suggest the most fruitful areas for future research from a financial perspective.

In this paper I will summarize past intensive culture economic research sponsored by the North Central Station, discuss present ongoing work, and make some general conclusions.

BREAK-EVEN ANALYSIS

When early research efforts began, SRIC systems were believed to have several advantages over conventional silviculture systems. SRIC systems could produce more biomass from the same acreage or the same quantity of biomass from less acreage. SRIC systems could also produce this biomass much sooner--5 to 15 years after establishment rather than the 30 to 80 years of conventional silviculture. Finally, the plantations could be regenerated by coppicing every 5 to 10 years from the same root stock, thus eliminating the need for periodic replanting.

A major disadvantage was that SRIC systems require large capital expenditures for higher quality, accessible land as well as for all the

[1/] Principal economist, USDA Forest Service, North Central Forest Experiment Station, Duluth, Minnesota

machines and installations required to perform the intensive management. This is particularly true for irrigated plantations.

Thus, the economic potential of alternative SRIC systems generated much discussion as the research program began and break-even analysis was selected to make preliminary economic evaluations (Rose 1976, Rose and Kallstrom 1976, and Rose 1977). With break even analysis, the compounded cost of growing and harvesting biomass is calculated under alternative management strategies. This in turn is compared to: (1) the physical yield (e.g., dry tons/acre/year) at a specified price, or (2) the price (e.g., dollars/dry ton) at a specified physical yield. The break-even point is the dollar value of the yield that just covers all compounded production costs.

Several different production systems were evaluated using this technique. The major variables were spacing, rotation length, number of coppices, cultural practices (e.g., replanting), and project length (table 1). Estimating production cost is extremely important in a break-even analysis. However, little actual data were available when the early analyses began, complicating the situation. Thus, each of the production systems was evaluated under low, medium, and high cost assumptions for two different initial site conditions: forest and pasture.

These early break-even results estimating the cost per dry ton of fiber produced are shown in table 2. Alternatives 5, 6, 7, 8, and 10 would be profitable assuming both a price of $25-$30 per ton for dry fiber and production costs at a low to medium level. Alternative 3 would be profitable only when the same prices are assumed and costs are low.

Table 1.--Specifications for intensive cultural alternatives

Alternative	Spacing (feet)	Rotations (number/ years)	Stand Origin	Project Length (years)	Regeneration Planting (age)
1	4x4	(1) 4 (4) 4	cuttings coppice	20	none
2	4x4	(2) 4 (2) 4	cuttings coppice	24	13
3	4x4	(1) 5 (3) 5	cuttings coppice	20	none
4	2x4	(2) 2 (4) 2	cuttings coppice	20	11
5	12x12	(1) 10 (1) 10	cuttings coppice	20	none
6	12x12	(2) 10	cuttings	20	11
7	12x12	(1) 15 (1) 15	cuttings coppice	30	none
8	4x4	(1) 15 (1) 15	cuttings coppice	30	none
9	4x4	(1) 5 (3) 5	cuttings coppice	20	none
10	12x12	(1) 15	cuttings	15	none

Table 2.--Break-even results of ten intensive culture alternatives

Alternative	Initial Site Condition	Cost Range/Ton of Fiber Produced (low)	(high)
1	Forest	$ 53.48-	$ 97.21
	Pasture	43.82-	84.71
2	Forest	54.89-	100.59
	Pasture	45.73-	68.75
3	Forest	29.82-	58.74
	Pasture	24.26-	51.56
4	Forest	512.78-	739.46
	Pasture	436.54-	652.02
5	Forest	21.68-	44.88
	Pasture	17.30-	39.18
6	Forest	22.23-	45.58
	Pasture	17.82-	39.88
7	Forest	27.11	
	Pasture	22.65	
8	Forest	26.86	
	Pasture	22.67	
9	-------	35.34-	60.64
10	-------	18.23-	42.08

Production cost per dry ton differs greatly depending upon the general cost level assumed. Also, these production costs were calculated from harvest yield assumptions based on experimental plots that were irrigated and fertilized annually (Ek and Dawson 1976). In contrast, most of the alternatives shown in table 2 assumed no irrigation and only periodic fertilization. If the management alternatives were carried out on sites where water and nutrients were limiting factors, the costs would be higher. Thus, these first analyses were crude and only roughly approximated the economic potentials of alternative production systems. Further investigations would be necessary using more sophisticated models when better production cost and yield information became available.

CASH FLOW ANALYSIS

As research on SRIC progressed, more realistic information became available on production costs and biological growth and yield, and land managers wanted more specific economic information about short-rotation systems, we chose to analyze them with a cash flow model (Lothner et al. 1981, Rose et al. 1981, and Ferguson et al. 1981).

We evaluated a few specific hybrid poplar plantations representing a likely range of spacings (4 by 4 feet and 8 by 8 feet), rotations (5, 10 and 15 years), and cultural practices (including irrigation and fertilization). Four alternative systems combined these variables (table 3). Each system consisted of 1,000 acres of cleared marginal agricultural land arranged in 10 tracts of 80 to 120 acres each.

Table 3.--Four alternative SRIC systems

Alternatives	Rotations: Length	Rotations: Stand Origin	Dry Yields: Per Acre/Year	Dry Yields: Total Yield at End of Rotation
	(years)		(tons)	(tons)
4 by 4 foot spacing irrigated and fertilized	10	cuttings	6.3	63
	5	coppice	7.2	36
	5	coppice	7.2	36
	5	coppice	7.2	36
	5	coppice	7.2	36
4 by 4 foot spacing not irrigated or fertilized	10	cuttings	3.2	32
	5	coppice	3.6	18
	5	coppice	3.6	18
	5	coppice	3.6	18
	5	coppice	3.6	18
8 by 8 foot spacing irrigated and fertilized	15	cuttings	6.3	95
	15	coppice	6.3	95
8 by 8 foot spacing not irrigated or fertilized	15	cuttings	3.2	47
	15	coppice	3.2	47

The important production and management activities of each system were identified by North Central scientists and the forester in charge of the only large-scale industrial SRIC plantation in the Lake States. Physical and dollar estimates were made for each of the production factors and yields as well as the relative uncertainty of each. Using a cash flow model, the financial performance of each system was evaluated by an internal rate of return (IRR) and present net value (PNV) criteria for a 30-year period. We also evaluated the sensitivity of the IRR and the PNV to both relative and absolute changes in the production factors and yields due to uncertainties.

Site preparation for the plantations included plowing, disking, and applying preplant herbicides. All these activities took place in late summer and fall prior to spring planting. Three cultivations and two applications of herbicide were used for postplanting weed control. Trees were irrigated by a traveling gun system that applied 10 inches of water per acre annually. Liquid nitrogen fertilizer was applied in the irrigation water at 100 pounds per acre per year. Plantations were harvested using whole-tree chippers for the 10- and 15-year rotations, and forage harvesters for the 5-year coppice rotations. Expenditures common to all alternatives included administrative costs, insurance, land purchase and sale, equipment cost, and taxes (income and property).

An annual inflation rate of 5 percent and a 10 percent discount rate were applied to all costs and returns.

Some of the cost and return assumptions follow:

Cost	Estimate (1979 dollars)
Land	$400 per acre
Planting stock	$ 80 per thousand
Fuel (diesel)	$ 1 per gallon
Labor (nonunion)	$ 4 to $ 6 per hour
Site preparation & weed control	$33.42 to $73.11 per acre
Irrigation	$99.74 per acre per year
Irrigation equipment	$387,700(initial investment for 1,000 acres)
Harvest	
Whole tree	$ 14 to $ 18 per dry ton
Forage	$ 8 per dry ton
Administration	$7,500 per year (for 1000 acres)
Property tax	$ 4 per acre per year
Income tax	28 percent of capital gains
Equipment insurance	1 percent of new price per year
Return	
Product value	$25 per dry ton

A more detailed account of the costs and returns is found in Lothner et al. (1981) and Rose et al. (1981).

With the assumed 10 percent discount rate, no alternative had a positive PNV. However, the two systems without irrigation and fertilization had positive after tax internal rates of return of 8 percent; the two irrigated and fertilized systems had negative internal rates of return (table 4). Economically, dif-

Table 4.--Initial investment and investment performance of four SRIC alternatives

Management Alternative	Initial Investment[1] (dollar/acre)	Present Net Value (dollar/acre)	Internal Rate of Return (percent)
4 by 4 foot spacing, irrigated and fertilized, short-rotations (5 to 10 years)	1,158	-2003.82	-0.4
4 by 4 foot spacing, not irrigated or fertilized, short-rotations (5 to 10 years)	770	- 236.78	8.1
8 by 8 foot spacing, irrigated and fertilized, long-rotations (15 years)	945	-2149.51	-1.6
8 by 8 foot spacing, not irrigated or fertilized, long-rotations (15 years)	557	- 200.30	8.1

[1] Includes land purchases, initial equipment purchase or lease, site preparation and planting costs, and administration cost for first two years.

ferences were small between rotation length and spacing options, but they were significant between the systems that were irrigated and fertilized and those that were not.

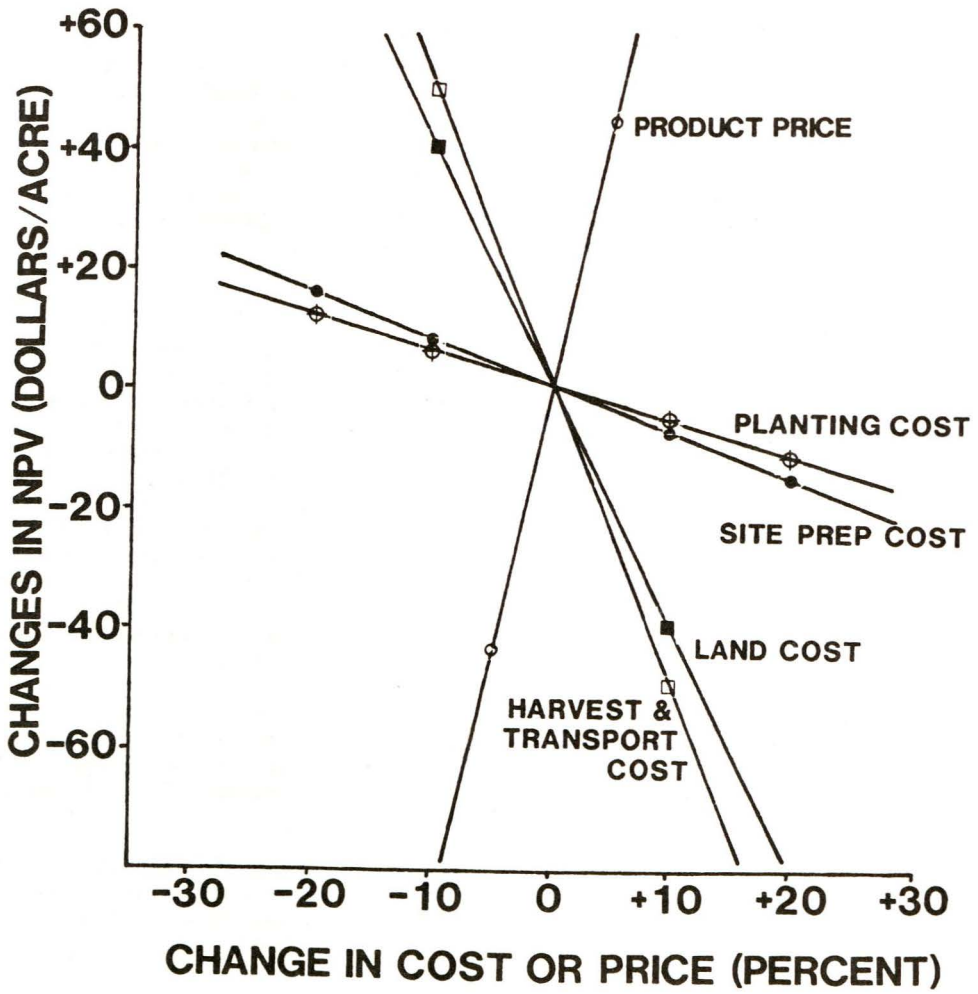
A sensitivity analysis can help identify how each cost or revenue factor affects the financial performance. In all four systems, the most important factor affecting investment performance was the product sale value. It was also one of the most uncertain factors. A change in yield, product price, or both, could substantially change the economic attractiveness of SRIC systems. For example, a 10 percent increase in mill prices from $25 to $27.50 per dry ton for chips for the 8 by 8 foot nonirrigated and nonfertilized system increased the PNV by 44 percent or $88 (fig. 1).

For systems without irrigation and fertilization, harvest and transport cost were the next important factor. For the 8 by 8 foot spacing alternative, a 10 percent change in harvesting and transport cost changed PNV by almost 25 percent or about $49 (fig. 1).

For the irrigated and fertilized systems, irrigation operating costs, primarily fuel, was the second most important factor affecting investment performance and would have to be substantially reduced for these systems to become financially attractive. Fuel costs represent 68 percent of the operating costs of the traveling gun irrigation system and a substantial fuel cost reduction with this type of irrigation system seems unlikely. However, new technology or changes in the irrigation schedule to only sporadic use (e.g., during establishment) could significantly reduce irrigation operating costs.

Site preparation costs and planting costs for any of the systems have little effect on PNV. For example, a 10 percent change in site

Figure 1.--Sensitivity of net present values (NPV) for 8 by 8 foot spacing, nonirrigated and nonfertilized system to relative changes in costs or prices.



preparation cost for the 8 by 8 foot, nonirrigated and nonfertilized system changes PNV by 4 percent or $8, while a 10 percent change in planting cost changes PNV by 3 percent or $6 (fig. 1).

The cash flow analyses suggested that nonirrigated and nonfertilized SRIC systems would be preferable to those that are irrigated and fertilized. But because the returns on investment would be low even for the nonirrigated and nonfertilized systems, these systems would be of interest only to individual users of wood biomass who can compare the potential of these systems to alternative sources of supply prior to making an investment decision.

In addition, the results indicate that the investment performance of the SRIC system is most sensitive to the product sale value (yield and product price), irrigation operating costs, and harvesting costs. Our current data concerning all these factors are inadequate. However, by pointing out their importance, we can focus our research efforts on them in the future. This may help us to reduce some of the important sources of uncertainty and make more informed future decisions. However, many of the factors depend on uncertain future events for which there will always be a limited present understanding.

However, some additional risks were not addressed by the cash flow analysis. For example, what are the risks of insect or disease outbreaks and what impact would they have on the investment performance? Or, what is the risk of failure, in unirrigated and unfertilized plantations?

RISK ANALYSIS

In a conventional cash flow analysis, mathematical formulas are used to precisely calculate financial performance estimates for various criteria by incorporating point estimates for each relevant factor included in the analysis. However, both the analyst and the decisionmaker--manager or scientist--know that behind these precise calculations are imprecise data. A great deal of uncertainty and/or risk[2/] always surrounds the basic information that goes into the analysis. Our past cash flow calculations have not adequately measured risks nor have we been able to directly incorporate risks into investment performance calculations.

We are currently cooperating with Michigan State University[3/] to model the risk inherent in SRIC projects. This work is based on some earlier work in risk analysis by Hertz (1964) and developed and reported on by others (Davidson and Cooper 1980; Economos 1968; and Hillier 1963). Incorporating risk analysis into a basic cash flow model requires three basic steps. First, a range of values is estimated for each of the production activities (e.g., a range of site preparation costs) and the probability or likelihood of occurrence of different values within the range. This is in contrast to the previous practice of estimating only the most likely value of each factor. Second, one value from the distribution of values for each factor is selected at random. The resulting set of selected values for all factors are combined in one cash flow analysis and the financial performance (e.g., internal rate of return or present net value) is calculated. Third, the second step is repeated over and over again to develop a probability distribution for the financial performance outcomes. This distribution of financial performance outcomes thus shows the probability of achieving any specified outcome--e.g., internal rate of return.

If we use two of the hypothetical SRIC systems mentioned earlier--the 4 by 4 foot and 8 by 8 foot nonirrigated and nonfertilized systems--we can illustrate what a risk model can provide in comparison to the conventional cash flow model. Let me emphasize that the numbers found in this section using the risk analysis model have no empirical value. They have been selected only to illustrate the risk analysis method.

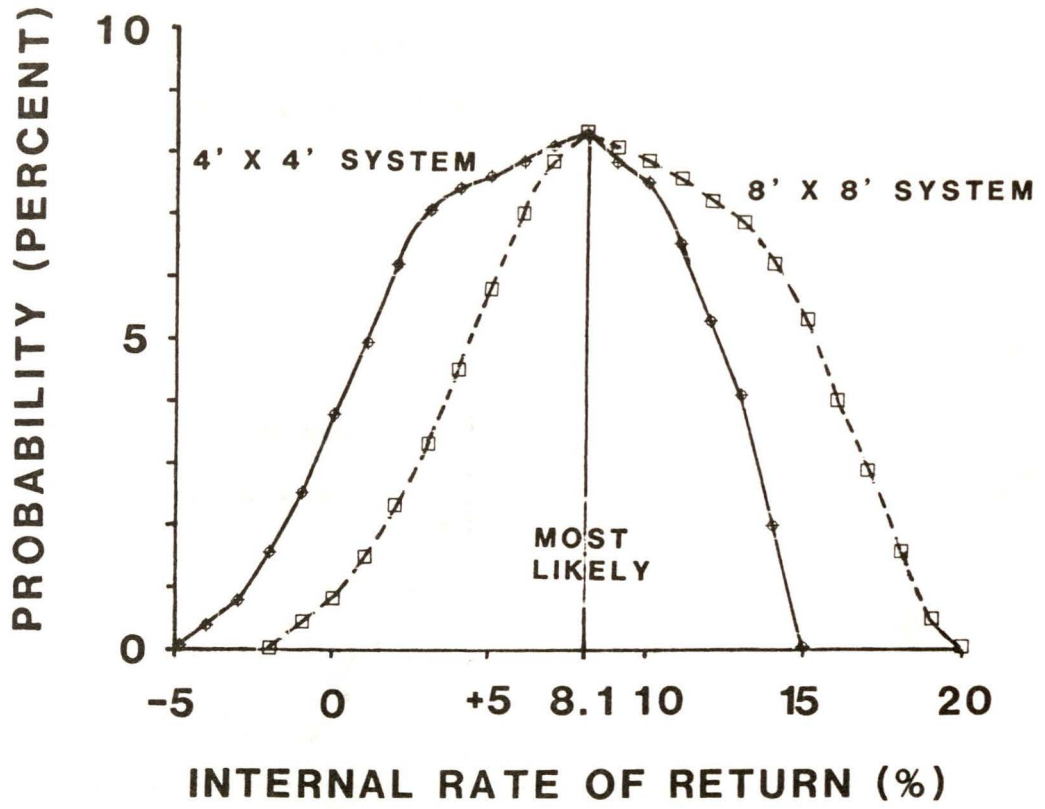
Using a conventional cash flow model, both the 4 by 4 foot and 8 by 8 foot nonirrigated and nonfertilized alternatives show 8 percent internal rates of return. Incorporating risk estimates provides the decisionmaker with estimates of the probabilities of achieving each possible value for the financial performance criteria--e.g., internal rate of return. Let's assume that when we incorporate risk into our analysis, the most likely outcomes for both the 4 by 4 foot and 8 by 8 foot alternatives remain the same as the conventional outcome--an 8 percent internal rate of return (fig. 2). In practice the most likely internal rates of return found using a risk analysis model would probably differ from the expected internal rates of return found under the conventional method using single point estimates. In the example above, we have

---

2/ In our discussions a risk situation is where the probability of an activity or event occurring is known or can be estimated; an uncertainty situation is where the probabilities of an activity or event occurring have not been estimated or determined.

3/ Paul A. Rubin, Assistant Professor, Graduate School of Business Administration, Michigan State University.

Figure 2.--Probability distributions of the internal rate of return for two hypothetical SRIC systems.



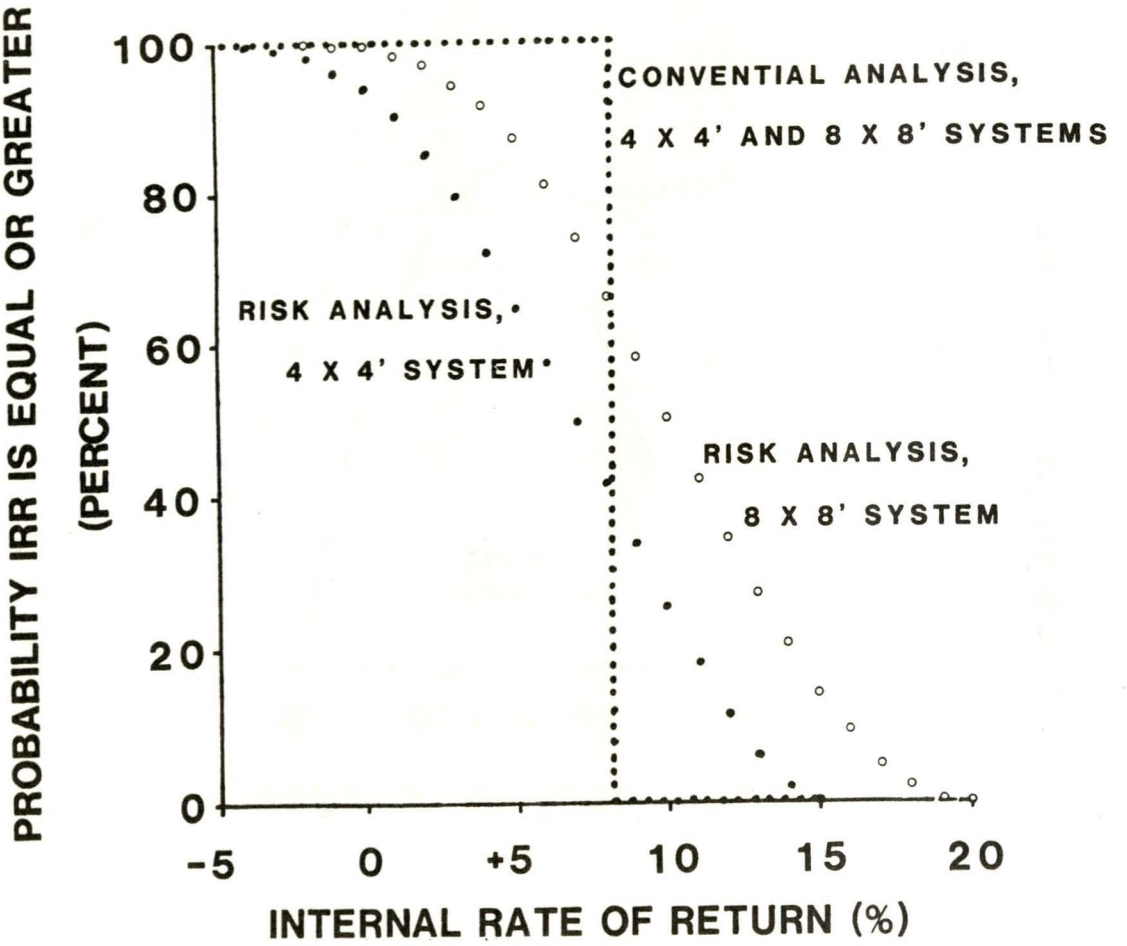
assumed both alternatives have about an 8 percent chance of achieving the 8 percent internal rate of return. The chances or probability of a zero or negative internal rate of return (no profit at all or even a loss) are much greater for the 4 by 4 foot system (fig. 2). (Remember that these numbers are for illustration purpose only and have no empirical value.)

Using a risk analysis method, the uncertainty of achieving at least a certain financial performance--i.e., internal rate of return--can be clearly displayed:

Internal Rate of Return	Probability of achieving at least the returns indicated	
Percent	Percent	
	8x8' spacing	4x4' spacing
0	99	94
2.5	96	83
5.0	87	65
7.5	69	45
8.1	66	42
10.0	50	25
12.5	29	8
15.0	14	0
17.5	3	0
20.0	0	0

We can compare the cumulative profile for the 8 by 8 foot and the 4 by 4 foot spacing systems using a risk analysis with the profile for these systems obtained under the conventional approach (fig. 3). Under the conven-

Figure 3.--Cumulative rate of return profile for two hypothetical SRIC systems using a conventional cash flow model and a risk analysis model.



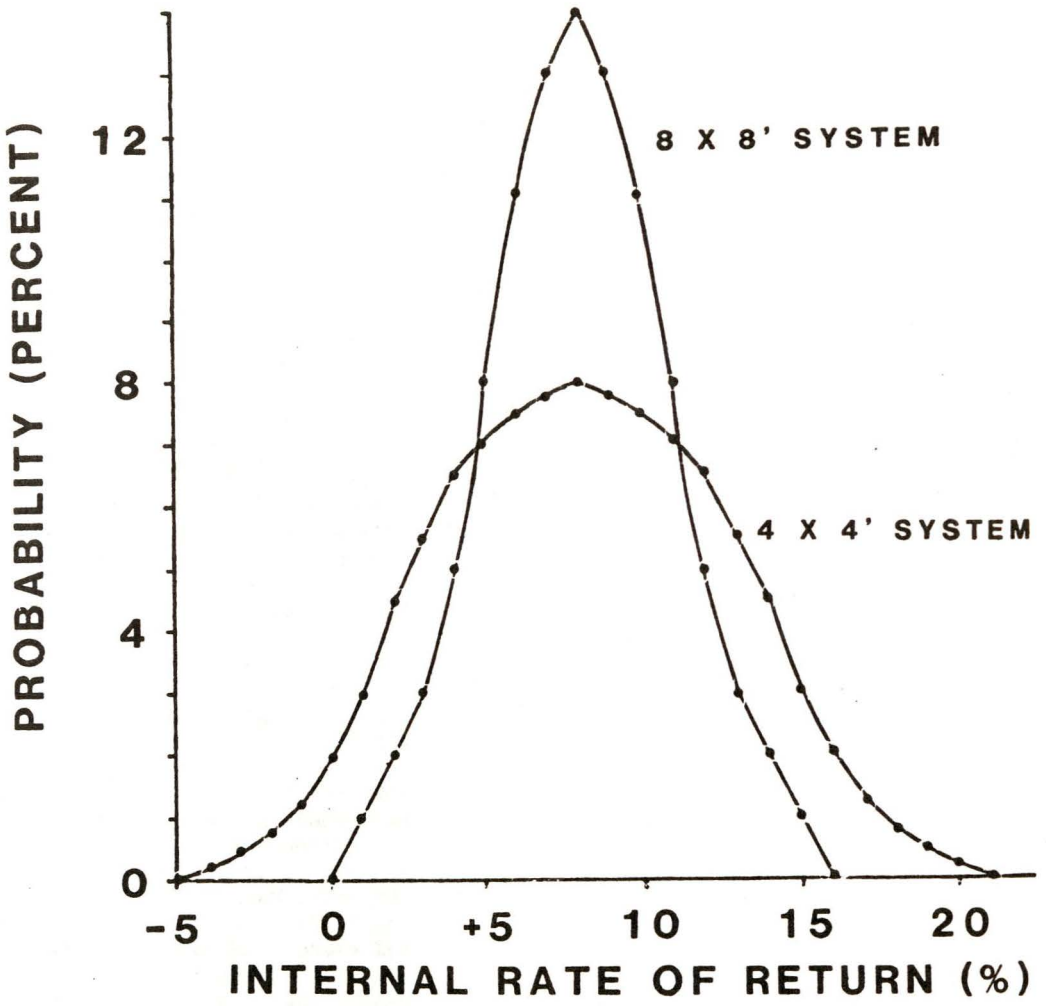
tional cash flow approach we would have no way to choose between the two systems because both produced an 8 percent internal rate of return. However, using risk analysis we can see that the 8 by 8 foot spacing would be superior to the 4 by 4 foot spacing. With the wider spacing we are 99 percent certain that we will not obtain a negative internal rate of return as compared to only a 94 percent chance with the narrower spacing alternative. In addition, we have a 66 percent probability of achieving at least an 8 percent rate of return with the wider spacing system as opposed to only a 42 percent probability with the narrower spacing. It is clear in this example that the wider spacing system is significantly better. Without accounting for risk in the model as with the conventional cash flow model, we would never know this.

This is not to say, however, that using risk analysis will always present information to the analyst for making clear choices. An analysis between two alternatives could result in one alternative being both more risky as well as having a greater opportunity for larger gains (fig. 4).

SUMMARY AND CONCLUSIONS

Economic analysis of SRIC at the North Central Forest Experiment Station has progressed during the past several years. After some early break-even analyses when basic data required for economic evaluation were almost nonexistent, we moved on to discounted cash flow analyses using sensitivity analysis to handle risks and uncertainties. Through these analyses we learned that using single estimates of production factor values, the monetary returns were fairly low. Through the sensitivity analysis we learned that financial performance was most sensitive to product price, product yields, irrigation costs, har-

Figure 4.--Alternative probability distributions of the internal rate of return for two hypothetical SRIC systems.



vesting costs, and land costs. These are all highly uncertain factors. The traditional and more certain management activities necessary to establish and grow hybrid poplars, such as site preparation and planting, were not as important as the previous factors. We also believe that considerable risk is involved in analyzing the financial performance of these systems where uncertainties are not directly accounted for within the system.

From a growing awareness of the importance of uncertainties we began to develop models to handle this problem. Work is still in progress so we do not have any real results. However, we can use hypothetical examples to show the kind of information that can be obtained by incorporating risk directly into the financial analysis.

Much work remains. If we recognize uncertainty, how do we build the model to allow managers to react to possible outcomes? And, once the model is developed, are there any real advantages for evaluating SRIC investment opportunities by this method? These will take considerable effort. Yet, the discipline of thinking through the uncertainties of the problem will perhaps in itself help the analyst assist the decisionmaker in making wise investment choices.

LITERATURE CITED

Davidson, Lynn B., and Dale O. Cooper. 1980. Implementing effective risk analysis at Getty Oil Co. Interfaces 1(6): 62-75.

Economos, A. M. 1968. A financial simulation for risk analysis of a proposed subsidiary. Management Science 15(12): 675-682.

Ek, A. R., and David H. Dawson. 1976. Yields of intensively grown Populus - actual and projected. In U.S. Dept. of Agriculture Forest Service General Technical Report NC-21, p. 5-9. U.S.D.A. For. Serv. North Central For. Exp. Sta., St. Paul, MN.

Ferguson, Karen, Dietmar Rose, David C. Lothner, and J. Zavitokovski. 1981. Hybrid poplar plantations in the Lake States - a financial analysis. Journal of Forestry. 79(1): 664-667.

Hertz, David B. 1964. Risk analysis in capital investment. Harvard Business Review. 42(1): 95-106.

Hillier, Frederick S. 1963. The derivation of probalistic information for the evaluation of risky investments. Management Science 9(3): 443-457.

Lothner, David C., Dietmar Rose, J. Zavitkovski, and Karen Ferguson. 1981. A financial analysis of poplar intensive cultures in the Lake States. In Energy from Biomass and Waste V: Symposium papers. p. 145-163. Institute of Gas Technology. Lake Buena Vista, Florida.

Rose, Dietmar. 1976. Economic investigations of intensive silvicultural systems. Iowa State Journal of Research. 50(3): 301-315.

Rose, Dietmar. 1977. Cost of producing energy from wood in intensive cultures. Journal of Environmental Management. 5: 23-35.

Rose, Dietmar, Karen Ferguson, David C.Lothner, and J. Zavitkovski. 1981. An economic and energy analysis of poplar intensive cultures in the Lake States. U.S. Department of Agriculture Forest Service, Research Paper NC-196, 44 p. U.S. Department of Agriculture Forest Service, North Central For. Exp. Sta., St. Paul, MN

Rose, Dietmar, and Robert D. Kallstrom. 1976. Economic feasibility of intensive cultures. In U.S. Dept. of Agriculture Forest Service General Technical Report NC-21, p. 96-107. U.S. Dept. of Agriculture Forest Service. North Central Forest Experiment Station, St. Paul, Minnesota.

FOUNDING CONCEPTS FOR TREE BREEDING AND RESEARCH

Hyun Kang[1]

Abstract.--Forestry research is a multidisciplinary venture and is typically a long-term effort with relatively low funding. The success of forestry research and tree breeding depends greatly on the coordination among forestry practitioners, research managers, and researchers. To coordinate they must have a common understanding of the research process. Therefore, the common understanding is the conceptual foundation for tree breeding and research. To develop a common understanding (1) the components of the research system must be differentiated in respect to their functions, and (2) the differentiated components must be integrated to generate the overall picture of the research system. Few general procedures are known for the differentiation and integration. Therefore, a tree breeding example was used to illustrate the differentiation and integration process, and to point out the importance of having a proper common understanding for forest tree breeding and research efforts.

To conduct meaningful research efficiently it is necessary for practitioners, research managers, and researchers to have a common understanding of the research process.[2] The common understanding will form the conceptual foundation for research activities. In the following sections I will (1) describe two views of the research process using a simple graphic model, (2) describe the components of the model using tree breeding as an example, and (3) use the model and the tree breeding example to discuss the differences between the views.

ALTERNATE VIEWS ON RESEARCH PROCESS

Different views of the research process exist because practitioners and researchers use different languages. Practitioners are concerned with practical problems and directly applicable solutions; researchers are concerned with researchable or solvable questions. I will use the term problem set (P) to represent the collection of problems defined by practitioners and solution set (S) to represent research questions and answers generated by researchers (fig. 1). Examples of problem set elements are increase biomass production, regenerate a species, and manage a plantation. Examples of solution set elements include problems in physiology, silviculture, and genetics; empirical studies; and causal analysis.

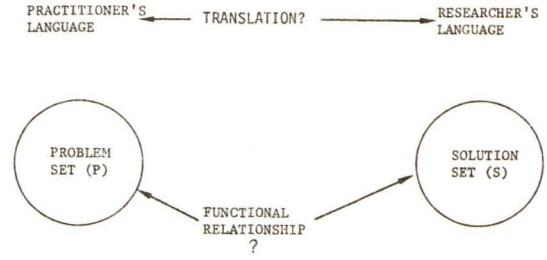


FIGURE 1. SET REPRESENTATION OF DIFFERENT LANGUAGES.

[1]Population Geneticist, North Central Forest Experiment Station, Forestry Sciences Laboratory, Rhinelander, WI 54501.

[2]The research system represents the collection of both physical and mental components of performing research. Research organization, research personnel, research process such as problem defining and solving are some examples.

Three different phases of a research process can be identified (fig. 1): application by practitioners, research, and the translation between practitioners and researchers. These three phases must be well balanced to make good use of the research activities. However, people have different views on the way the translation phase should be handled.

In one view, the translation is considered as a temporary phenomenon that occurs as the need arises. This view is possible only when the functional relation between the two sets (P and S) is primarily additive. According to the additive functional relation, a research effort that achieves a 5 percent increase in biomass production under the experimental set-up would assure an equivalent gain in an applied operation. Therefore, by adding up the results of all other research efforts one should be able to generate much greater gain in operation. A research manager holding this view, when faced with budget reduction, could simply take out any part of the research operation without influencing the effectiveness of the rest of it (fig. 2A).

In an alternative view the translation phase is viewed as a unit that evolves. The interaction among different disciplines and research efforts is considered as a critical component of the function (fig. 2B).

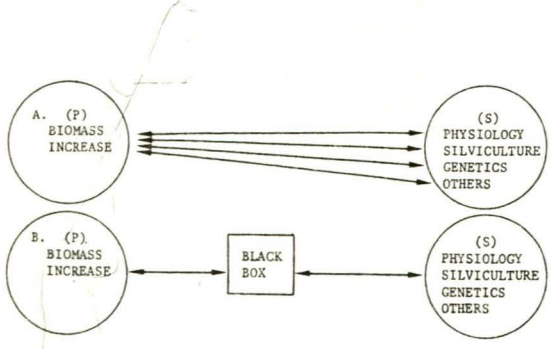


FIGURE 2. ALTERNATIVE VIEWS ON THE FUNCTIONAL RELATION BETWEEN PROBLEM SET (P) AND SOLUTION SET (S). BIOMASS INCREASE IS USED AS AN EXAMPLE.

A. ADDITIVE VIEW OF THE FUNCTIONAL RELATION BETWEEN THE TWO SETS. NO INTERACTION AMONG DIFFERENT RESEARCH DISCIPLINES IS CONSIDERED CRITICAL.

B. FUNCTIONAL LINKAGE BETWEEN THE TWO SETS THROUGH A BLACK BOX. INTERACTION AMONG DIFFERENT DISCIPLINES IS CRITICAL. TRANSLATION AND PACKAGING IS PERFORMED IN THE BLACK BOX.

Few are likely to endorse the simple additive view, but that does not necessarily mean the presence of strong efforts to improve the quality of the translation phase. The lack of effort to develop and improve the translation phase is equivalent to enforcing the additive view. Therefore, the true question is how can a good translation phase be created and improved?

A firm conceptual foundation is necessary to create an evolving translation phase. The formation of the foundation takes two steps: (1) the components of the research system must be differentiated in respect to their functions--from the differentiation the members of the research system can understand the specific roles of different aspects of the system; and (2) the components must be integrated to generate the overall picture of the system. Through repeated differentiation and integration the conceptual foundation for the research will become firmer, yet remain flexible.

Few general procedures are known for the differentiation and integration. Therefore, I will use a tree breeding example to discuss the procedure and will begin by presenting a potential gain from tree breeding.

POTENTIAL GAINS FROM BREEDING

The field of genetics has advanced greatly and breeders can now predict the gain from a specific breeding technique. As a current example, a Populus clonal comparison study at Harshaw farm showed that selecting 1 or 7 out of 15 clones yielded 115 percent and 47 percent predicted gains in volume index (D^2H), respectively (Hansen et. al. 1983). The clonal selection did not include further breeding. We know from many crop and animal experiments that subsequent breeding efforts could achieve much greater gains than can be obtained in a single generation of selection. The gain in volume index could exceed 200 percent in 3 or 4 generations. This example suggests that Populus breeding has a great potential for increasing biomass production. Similar increase in productivity can be readily demonstrated in other tree species. No doubt breeding is an important means of increasing forest productivity. To achieve the increase in productivity of various tree species, breeders must classify the activities in the solution set by asking the following questions. First, how can such yield increases be realized? Second, can the selection process be made even more potent?

To realize the potential yield increase the environments for breeding and for operation must be relatively homogeneous and constant. The

homogeneous environment enhances the selection efficiency of a given generation, and the constant environment makes repeated directional selection possible. If the direction of selection has to change from generation to generation, recurrent selection will become meaningless and the cumulative genetic gain will never be realized.

Conventional forest tree planting sites are very heterogeneous, and two contrasting approaches to tree breeding are possible. Despite environmental heterogeneity, trees can be bred using conventional extensive cultural methods--the genetic gain will be small, but small energy inputs will be required. Or breeders can use intensive cultural efforts and minimize environmental variability--genetic gain will be greater than with extensive culture, but large energy inputs will be required.

To make the selection process more potent the selection techniques must be improved. In the above example the selection technique used was the ranking of D^2H measurements of clones. Such measurements are subject to many sources of error. Any reduction of the ranking errors would improve the potency of the selection. The error can be reduced by identifying the components that make up the trait of interest (D^2H in this example) and by understanding the functional relation between the components and the trait. This will require additional basic research on the causes of the trait response. The basic research results may or may not be directly applicable to field operation. In contrast, breeding is empirical research designed to determine the nature of responses for a given set of causes (or factors). The two research types differ depending on whether the emphasis was put on the study of the causes or on that of the responses.[2]

---

[2]Definitions of basic and empirical research are, of course, arbitrary. There could be many more classes in the same classification scheme, or even completely different types of classifications. For example, contrasting basic vs applied, and theoretical vs empirical simultaneously would be more desirable in the strictest sense. A rigorous treatment of the classification, however, would require a separate discussion. In this presentation, therefore, the contrast between direct meaning of the terms, basic and empirical, is of secondary importance. It is more important to note the contrast between the meaning of the terms as they are defined here.

From the examination of the two questions four distinct elements of a solution set have been generated: extensive culture, intensive culture, basic research, and empirical research. In the following sections I will discuss the relation between breeding and extensive culture, intensive culture, and basic research. I will not discuss empirical research as an independent subject but rather I will mention it as it relates to the other elements.

BREEDING UNDER EXTENSIVE CULTURE

The justification for breeding a species depends greatly on the size of the planting program for that species. The unit genetic gain under extensive culture is small. But, because current planting is large, this small unit gain will affect a large number of planted trees and result in a large overall increase in productivity. Another requirement for breeding under extensive culture is that plantation establishment should require little cultural effort (low energy input). The foregoing two requirements limit hardwood, including Populus, breeding under extensive culture in the Lake States.

Under extensive culture the research approach is primarily empirical. Although breeders use information from basic research to determine factors to examine, the research results usually do not explain the causes of the observed responses. The research and the use of research results are also opportunistic and strategic. Instead of investigating the causes of the trait responses, breeders search for working rules that will make the breeding successful based on available information. At the same time, breeders leave room for rule changing as more information becomes available. Therefore, breeders do not strive to develop a single genotype that is superior to others on all available planting environments.

A typical breeding scenario under extensive culture begins with provenance testing--matching the available breeding stocks to different environments. From the provenance testing results, breeding and seed zones are defined. Once breeding zones are defined, breeders limit the breeding stocks in the zones and begin recurrent selections within each zone. The breeding zones reduce environmental variability which enhances the selection efficiency at the given generation. By limiting a particular set of breeding stocks within the zone while making recurrent selections the continuity of breeding environment can be maintained. Reducing environmental diversity and maintaining

continuity of the breeding environment is also used in intensive culture. In extensive culture breeding stocks are distributed to different environments, whereas in intensive culture the environment is modified to support superior breeding stocks.

Breeding under extensive culture is a logical answer to the current demand for improved plantation management technology with low energy input. The breeding effort is a reaction to the current demand. The approach is realistic because both the domain of activities and the range of the results of the activities lie within the scope defined by the current demand. In a realistic approach the success of the breeding is measured by how well the activity meets the demand. A typical result of a realistic breeding approach is the gradual and cumulative genetic gain.

BREEDING UNDER INTENSIVE CULTURE

Realistic approaches to breeding and research do not suggest revolutionary concepts that could lead to the change in the demand itself. In many cases technological breakthroughs accompany changes in the type of demand. The basic requirements for a breakthrough are imagination and futuristic views. Dawson and Hutchinson's (1973) description of intensive culture is an example. Intensive culture is the proving ground for futuristic cultural models. The most important fact that has been frequently overlooked is that futuristic approaches are usually not realistic. It is not necessary to try to justify futuristic models using realistic arguments. In all likelihood, if a futuristic model is justifiable on a realistic basis, it is no longer futuristic. Either the breakthrough already has occurred or the model was wrong. In any event, no new breakthroughs will come from the model. Dawson and Hutchinson (1973) spoke about the transition from "hunting and gathering" to domestication. Did ancient farmers begin domestication because they had economic justification? If they had tried to economically justify their activity, would modern agriculture have evolved?

The basic assumption of the futuristic intensive culture model is that once one or more economically advantageous cultural systems are developed, tree growers will use the models and divert a certain fraction of their practices to the intensive culture system.

The primary function of intensive culture is redistribution of forest land productivity. Increased productivity of certain sites may not increase overall productivity of forest land. Therefore, intensive culture can be justified with or without future timber shortage. The number of Populus trees planted annually in the Lake States or the ease of establishing Populus stands in wild environments are irrelevant to the decision to breed Populus under intensive culture. The justification should come from the growth potential, convenience for breeding and propagation, available knowledge on the species, etc.

Selection can be effective in intensive culture because the environment is relatively homogeneous and of high quality. However, the breeding still has to be strategic and breeders must be concerned about factors that influence the long-term success of breeding. For example, a well structured large breeding population(s) must be maintained.

The initial step of breeding under intensive culture is similar to that of extensive culture. For example, with Populus the program may begin with tests of clones or progenies at various locations. From the testing the breeder can match breeding stocks and sites. Using the testing materials or their progenies, breeders can select further to generate clones to be released immediately. However, the immediate release of superior clones is not an integral part of futuristic breeding under intensive culture. The futuristic breeding includes activities such as repeated selection and breeding of trees that perform better under given levels of fertilization, irrigation, and other cultural activities. The selection criteria will include many important growth components identified by the basic research. Without the futuristic breeding under intensive culture, the 200 percent gain in D^2H will not be realized. The research is primarily empirical. Even under intensive culture most breeding research does not explain the causes of the responses.

BREEDING ASSOCIATED WITH BASIC RESEARCH

Breeders cannot improve their selection and breeding techniques without supportive basic research. Under the most ideal conditions, the pool of information generated by basic researchers will be large and continuously updated and improved. Furthermore, there should be a harmony in different levels of research between very basic biological work and strategic breeding formulae. To create

such harmony requires a common ground where researchers can exchange information. Larson and Gordon (1969) have viewed intenive culture as such a common ground where technology transfer can occur between scientists.

Although the final recommendation of Larson and Gordon and Dawson and Hutchinson were the same, the emphases of the two ideas were different. Larson and Gordon emphasized the process by which the basic information can be used at higher levels of the application; it does not dictate the final destination of the information. Dawson and Hutchinson, however, emphasized generating a cultural model that maximizes return. Their approach does not discriminate the type of information used to develop the cultural model.

The breeding associated with basic research is different from breeding for production. Breeding population size in research may be small, and the number of species worked on small. In fact, for given resources it is best to generate integrated information on one or a few species. Populus is very desirable as an experimental species.

A SYNTHESIS

After studying the differences among extensive culture, intensive culture, and basic research, a tree breeder or forester may take one of the following approaches to develop an integrated view on the research system. First, he may assign economic priorities to the three categories and choose the one with highest priority (additive approach). Second, he may take all three categories and try to balance their strength (balancing approach).

A close examination of the three categories will readily show that the additive approach is difficult to accept in forestry research. For example, consider the choice between extensive culture, which is realistic, and intensive culture, which is futuristic. It is unlikely that breeders can afford to work with futuristic problems exclusively while ignoring realistic problems. Only by balancing the realistic and futuristic problems can breeders quickly respond to future trends and suggest new directions in timber management while also solving immediate problems.

The additive approach is also difficult to accept because the demands of beneficiaries of breeding and research tend to be complex. For example the tax payer may wish some immediate benefit from government research such as improved genotypes and technical assistance on managing his woodlot. At the same time he may wish the government to develop an advanced, more efficient system of producing woods while allowing room for conservation. Therefore, to satisfy the needs of tax payers, government research must include both realistic and futuristic components.

The difference between the additive and the balancing approach can be made clearer using graphics. Assume that it is possible to assign values to the research needs expressed in the problem set and research activities in the solution set such that they can be represented in a two dimensional cartesian coordinate (fig. 3). In the additive approach a one-to-one correspondence exists between points of the two sets (fig. 3B). The coordination within the solution set is not essential and the set simply represents the collection of points, and the size of the solution set is the same as that of the corresponding problem set. The main advantage of the additive approach is that individual research can be economically justified independently.

In the balancing approach the mass centers of the two sets correspond to each other (fig. 3C). Although the members of the two sets could correspond to each other, such correspondence is not the fundamental requirement. The solution set is more than a collection of points. It includes a strong structure of coordination. Because the solution set and the problem set communicate through their respective mass centers, the boundary of the solution set could be much larger than that of the problem set. In this approach, the primary unit of the economic justification is the entire research system.

When the research needs in the problem set change randomly, the corresponding points in the solution set of the additive approach must be adjusted accordingly (fig. 3D) some of the ongoing research must be discarded and some new research must be begun. No change is likely in the balancing approach because the mass center tends to remain constant under random changes (fig. 3E).

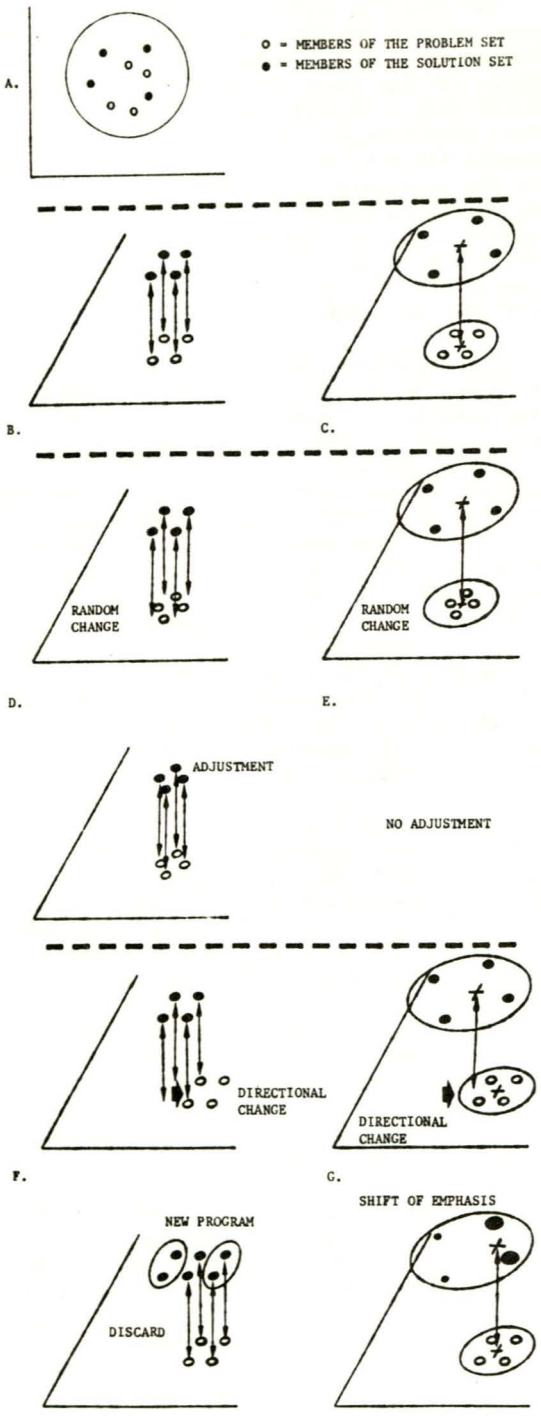


FIGURE 3. A GRAPHIC REPRESENTATION OF THE RELATION BETWEEN PROBLEM SET AND SOLUTION SET. B., D., AND F. REPRESENT ADDITIVE APPROACH, AND C., E., AND G. REPRESENT BALANCING APPROACH.

A. RESEARCH NEEDS AND RESEARCH ACTIVITIES IN CARTESIAN COORDINATES.

B. AND C. EXPLODED VIEW OF RESEARCH NEEDS AND RESEARCH ACTIVITIES. AT INITIAL STAGE RESEARCH NEEDS AND RESEARCH ACTIVITIES ARE ASSUMED TO BE WELL ALIGNED.

D. AND E. RANDOM CHANGE IN ELEMENTS OF THE PROBLEM SET.

F. AND G. DIRECTIONAL CHANGE IN ELEMENTS OF THE PROBLEM SET.

When the research needs in the problem set change directionally, adjustments are needed for both approaches. In the additive approach the same adjustments are necessary as for random changes, some projects must be discarded and new ones begun (fig. 3F). In the balancing approach the emphasis must be changed such that the mass center of the solution set can be shifted (fig. 3G). Because the boundary of the solution set is larger than that of the problem set, it is unlikely that the mass center of the problem set will move beyond the boundary of the solution set. Therefore, the problem set of the balancing approach will continue to have some immediate solutions to the new problems.

Although the balancing approach has many conceptual advantages, it is difficult to organize a solution set and align its mass center with that of the problem set. The additive approach is much easier to create and is very effective for short-term projects with abundant funding. Forestry research is basically a multidisciplinary venture with long-term efforts and low funding. Therefore, forestry researchers cannot afford to pay the price for the discontinuity associated with the additive approach.

To make the balancing approach work we must create and improve a black box, which is a vehicle for coordination (fig. 2B). Although no general procedure has been outlined for creating and improving the black box, two things are required for its successful evolution. First, researchers must have a common understanding of the research system to be used. For example, consider the Research and Development program on intensive culture. Three general areas of research will be necessary to make the program functional: (1) cultural techniques, (2) physiology, and (3) breeding. In the past, the program lacked breeding efforts but in the future, the success of the program cannot be guaranteed without it. In fact, the balancing of the three different areas of research is the key to the future success in the Research and Development program. Second, forestry practitioners, research managers, and researchers must be willing to cooperate to make the research system work. Every research system will always have some deficiencies but the deficiencies cannot be the excuse for lack of cooperation. For example, the Research and Development program still lacks a breeding program and will lack physiology research on growth characteristics of Populus but that should not prevent geneticists and physiologists from contributing to the program. Furthermore, research administrators must continue their efforts to balance the program.

☆ U.S. GOVERNMENT PRINTING OFFICE: 1983-666-624/5023

It may be helpful to think of the evolution of coordination in terms of the group selection concept in organic evolution. At the individual level, the traditional Darwinian concept of fitness works. In group selection, however, altruistic members of the group are equally important as the fittest members of the group to enhance the average fitness of the group under the given environment. If a research group becomes incoherent due to lack of coordinates and altruism, an excellent piece of research will be lost in a bag of unfit information.

LITERATURE CITED

Dawson, D. H., and J. G. Hutchinson. 1973. Farming for fiber, Wisconsin Conservation Bulletin, May-June, p. 24-26.

Hansen, E. A., D. A. Netzer, M. E. Ostry, H. M. Phipps, L. M. Moore, and J. Zavitkovski. 1983. Establishing intensively cultured hybrid Populus plantations for fuel and fiber. GTR-NC-78 (In press).

Larson, P. R. and J. C. Gordon. 1969. Photosynthesis and wood yield. Agriicultural Science Review, First Quarter, p. 7-14.

U.S. Department of Agriculture, Forest Service.
Intensive plantation culture: 12 years research. Gen. Tech. Rep. NC-91.
St. Paul, MN: U.S. Department of Agriculture, Forest Service, North Central Forest Experiment Station; 1983. 155 p.

A collection of papers summarize the status of knowledge for growing hybrid poplars in a short rotation intensively cultured system. The research included studies of propagation, physiology, culture, engineering, insects and diseases, and economics.

KEY WORDS: Short rotation, energy plantations, Populus spp., Alnus spp.